FRONTIERS OF SCIENCE

CARL T. CHASE

Frontiers of Science

PLATE I

A product of research a
a tool for science.

FRONTIERS OF SCIENCE

By

CARL TRUEBLOOD CHASE, PH.D.

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To

KARL TAYLOR COMPTON

WHO FIRST INTRODUCED THE AUTHOR TO
THE FRONTIERS OF PHYSICAL SCIENCE
THIS BOOK IS RESPECTFULLY DEDICATED

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CHAPTER I

THE WILL TO KNOW

As these lines are being written the morning papers announce the conquest of the Asiatic peak called Minya Konka. In Europe an expedition is laying plans for a new assault on mighty Everest. Physicists are carrying cosmic-ray electroscopes to inaccessible mountain heights. Men are risking and sometimes losing their lives in balloon flights to the stratosphere, and are descending far below the surface of the ocean in diving chambers. Astronomers are turning their telescopes toward the depths of space, trying to see a little farther, trying to learn a little more of the structure of our universe, and of its past and future. Others are busily unravelling the secrets of the atom from a study of spectrum images on photographic plates. Doctors of medicine are patiently seeking the solution of problems that often appear to have no solution. Explorers are venturing into the far North and the far South, while others dig in the inhospitable desert regions of the earth.

It is sometimes difficult to justify the cost in money and in human effort of scientific investigation, especially if this justification is to be made to a man of the genus "practical." Such a man, however, can always be reminded of a question that he himself once asked: "Daddy, what is the wind?"

The challenge of the unknown is not to be disregarded, and the will to know has always been one of the most significant attributes of human life. A characteristic of childhood, it does not invariably fade with the advancing years. If the child is spanked for asking too many questions he will merely address his inquiries to someone else; if the man can find no one who is able to give him the information he is seeking, the chances are that he will set out to discover this information for himself, and incidentally for his fellowmen as well.

Scientific investigation often has a justification that appeals especially to the practical or unimaginative man.

Everyone knows what science has done for him. Whenever Mr. Doe turns on the electric light, settles into his armchair, and tunes in his favorite radio program, he is acknowledging his debt to science. When he steps on the starter button and hears the engine of his car pick up under its own power he pays tribute to research. Nearly everything he does is in some way dependent on investigations which at one time might well have been looked upon as quite impractical. If he is ill his chances of recovery are much greater because of some purely scientific piece of research, for one of the greatest triumphs of research has been the lengthening of human life. Whether or not Mr. Doe believes in vivisection he will, if his life is in danger, not refuse medical assistance which has been made possible by experiments performed in the laboratory on animals.

Mr. Doe, however, generally pays his tribute to science unconsciously, and confines his conscious thoughts on science to a wish that physicists would decide what the atom really is so he might know what to think, and that astronomers would succeed in giving him a clear answer to the question as to whether the earth is the only inhabited part of the universe. Accordingly he will read, possibly with some dismay, that the latest attempt to smash the atom has cost let us say fifty thousand dollars to date, or that Professor Blank has worked for thirty years in an effort to measure something that is far too small ever to be seen by anybody. This in spite of the fact that Mr. Doe is enjoying the fruits of work that was similarly ridiculed by one of his ancestors a century ago. But if Mr. Doe is a forward looking individual he will realize that much of the purely scientific work being done today will bring to his children a degree of material welfare that is now impossible for himself, even with his own immense heritage of scientific achievement.

At present research and exploration are inspired partly by the will to know, which is a common possession of all humanity, and partly by a desire to assist mankind to a better, a more comfortable, and more pleasant life. There may be added, generally in small amount, the personal desire of the investigator for fame and fortune; and of late years, especially in certain fields, the faith placed in scientific investigations undertaken by the industries with definite expectations of early financial reward.

In the long run, however, the will to know has been the principal force urging men on to research and exploration. It has been invoked to prove that although the earth is astronomically quite insignificant, the mind of man with its demand for an understanding of things in nature makes of his terrestrial abode one of the very few places, possibly the only place of supreme importance in the universe. The will to know is present in different amounts in every human brain. It occasionally exists in such intensity that all obstacles are overcome. Such was the case with a Columbus. Occasionally it exists with great strength in the mind of a genius and we have a Newton or a Pasteur. It is such a general and persistent trait in humanity that lacking a Newton still the law of gravitation must sometime have been discovered.

Coupled with the will to know is the will to attain the unattained. The former does not entirely explain the zeal of mountain climbers who return year after year in renewed attempts to reach the summit of the world's highest peak.

The soul of man is a very difficult thing to comprehend. In spite of the fact that some contemporary biochemists would like to be able to account for it by means of a few chemical equations, it is safe to say that no one can tell us just what a human soul is, where it came from, or why it exists. The soul must be described by its properties. It enables man to appreciate beauty. It demands fidelity to friends and directs whatever religious faith a man may have. It is the seat of the will to know and of the desire to

attain the unattainable. It has thus controlled to a large extent whatever progress the human race has made toward its ultimate destiny, so far as this progress has not been the result of blind chance. For if behind the scenes there is a plan, if mankind has not risen to his present high estate as the result of the throw of a pair of cosmic dice, this plan must be made manifest through what is called the human soul.

The will to know is not by any means a recent development. Only the way of approach to knowledge has changed with the advancing years.

At various times in history man has called first upon divine revelation, later on cold philosophy, and finally on colder experiment to give him ultimate truth. As the point of view has changed so have changed the beliefs of man concerning his origin and destiny, as well as his thoughts on the everlasting why of the universe into which he has been born. Thus the changing approach to knowledge has caused upheavals in man's concept of truth, whereas the fundamental facts of human desire for knowledge and for conquest of the material world have never changed.

"In the beginning was the Word, and the Word was God." The biblical story of creation is an account of one of the first attempts to formulate a definite theory of cosmogony and shows that the will to know was urging men onward even at the early date when histories were written on slabs of stone. This particular theory has been read and accepted by more persons than have all other theories of cosmogony combined. The cosmogony of the Bible has lasted unchanged for

countless centuries, and was probably accepted long before the Bible was ever written.

In the early years of our race the existence of a personal God was accepted without question. God the benevolent, God the all-powerful, was believed to have created the world for the sole purpose of providing a comfortable abode for His beloved creation, man. How was this known? Repeatedly we are told in the Old Testament that "God appeared unto him and revealed to him" that He had done or would do so and so. With a belief in God well nigh universal, the word of God was accepted practically without question. It was assumed that He had taken a handful of cosmic dust, kneaded it like so much dough, shaped it into lumps of the proper size and shape, and pronounced over it all a spell known only to Him. The result of this process was the world, the sun and moon, the planets and the stars, and man.

It was characteristic of the time that no determined attempt was made to discover how much truth the idea might contain. The will to know, having come to flower and produced fruit, had gone to seed, and the seeds were not to germinate for centuries. Indeed, with the meager knowledge of natural law which was at their command early peoples had no way of inquiring into the truth of the biblical cosmogony, nor did they possess any standards by which the truth of such a theory could be judged. Natural law was summed up in the statement: "God is all-powerful." The world had been created and was now complete. The story of creation had been revealed to man and had been recorded. There lay truth.

To many moderns, particularly to many modern scientists, these ideas seem naive in the extreme, especially when the known facts relating to the mechanics of the solar system are compared with the beliefs of earlier days. The earth was supposed to be flat, and bounded on all sides by unknown horrors. Above was heaven, below was hell. The system was complete and answered every need. The sun, moon, planets, and stars were caused by the mighty hand of the Creator to move for the benefit of man and for no other reason. Anyone wishing to know anything about the cosmic scheme had only to pray for this knowledge. True, not a great deal of this sort of curiosity existed; instead, men of the time were more often concerned about their fate in a coming battle.

The biblical cosmogony was in some ways extremely satisfactory. It was gratifying to human pride to know that heaven and earth had been created for man alone, and the stars for his enjoyment. It was also very pleasing to early men to know that themselves and their world had been placed at the geometrical center of creation.

Some contemporary scientists and philosophers hold the view that with the acceptance of the Copernican theory the first step in man's fall from significance had been made and that this fall has continued with each new scientific discovery, until now they would have it that man is a mere accident, a transient cosmic experiment. Others hold that this view is a result of shallow thinking; for how can the philosophical importance of a human being depend on such things as geometrical position? Accepting for the moment the

view that men of biblical times had in general the correct idea, i.e., that a God had created man and intended to develop him for some future purpose known only to the Creator, it presumably is possible that God's purpose might better be served by placing man and his abode at the very edge of the universe, or at any conceivable position within it, not necessarily at the center. If indeed the universe was created for man, then the significance of man should increase as the grand scale of the universe is unfolded by scientific discoveries. Those moderns who insist that God and science are mutually exclusive are fully as prejudiced as were the early religious dogmatists. It is prejudice and science that cannot continue to coexist.

The ideas recorded in the book of Genesis persisted in practically unchanged form in most parts of the world until well into the seventeenth century. In the meantime, however, the will to know was cropping out again in a small part of the world, and was producing a new development of great significance in the age-long search for truth.

During the time that has been called the Golden Age, civilization in Greece achieved a high degree of perfection. Architecture, sculpture, and literature reached new heights. Mathematics, especially geometry, was studied intensively. New theories of government were evolved. Living conditions, at least for the upper classes, were greatly improved. Those to whom original thought was possible possessed sufficient leisure to exercise their minds and philosophy grew and thrived, especially in the great schools such

as those headed by Plato and by Pythagoras, until philosophy and logic came to be regarded as the only correct approach to new knowledge. Since neither benevolence nor perfection were attributes of many of the gods in their pantheistic religion, the Greeks were interested more in philosophical perfection than in the revelations of one benevolent and omnipotent God. Speculation, not revelation, was the approach to truth. New knowledge was to be obtained by thinking and philosophizing about what was already known, or more correctly, what was believed to be true.

Possibly the best example of such reasoning can be found in Euclid's geometry. The truth of every proposition therein depends on the truth of such assumptions as that a straight line is the shortest distance between two points, an assumption that has never been proved except in very limited and special cases. No one has ever claimed that God revealed to him any such property of a straight line. Instead it was assumed, or regarded as known, that straight lines had such properties. In astronomy, the orbits of celestial bodies were supposed to be circular because, since these bodies must be perfect, their orbits should also be perfect, and the circle was the most perfect curve that could be drawn. Similarly it was "known" that the earth was at the center of all creation; men and gods, the most important things in the universe, were naturally given the position at the center, dominating the whole. The gods dwelt on earth but on a mountain peak, not so far removed from human beings either in space or in behavior as the God of the Bible.

The will to know was strong in Greek minds of the Golden Age, and led them very far indeed. But just as their insistence on philosophy and logic as the source of all knowledge differed from ideas of revealed truth, the Greek ideal was later to be displaced by still another source of knowledge, scientific experiment.

Perhaps the most desired bit of information, the very source of the will to know, is and always has been the desire of man to know whence he came, where he is going, and what his place in the universe is. Early peoples had been proud of their spiritual descent from God the Father; the Greeks were fully as proud of the power of the minds possessed by mortal men. If their gods had stepped downward, human beings had taken in the meantime a corresponding step upward.

Today we know that the Greek philosophers were often as much in the wrong as were the early peoples who accepted each word of the Bible as irrefutable and final truth. Pythagoras could well argue that the distances of the planets increased in a musical or harmonic progression. Aristotle might prove by the most beautiful logic that heavy objects fall more rapidly than light objects. What the Greeks failed to realize was that argument alone never caused objects to behave in such a way. To them it seemed foolish to use their eyes when the use of their minds resulted in such perfect and logical arguments and theories. They would have found more of truth if they had used their eyes a little more and their minds a little less.

Once again the will to know had blazed up, burned

with a glorious flame for a time, and then subsided. And as before, the results of this flare-up dominated thought for centuries, becoming so firmly established as to retard the next blooming of the flower of discovery for many years.

During the period of the Renaissance a great spiritual awakening came to Europe. Although this period is generally mentioned by historians in connection with the study of art and literature, it is also important in a quite different field. The Renaissance has given us beautiful paintings, impressive architecture, and great literature; it has also given us modern science.

The scientific awakening came at the very height of the Renaissance, when this period of history was already some two centuries old. It may be that the will to know, whetted into new activity by the general stimulation of thought, began to disclose errors in the inherited philosophy and knowledge of the day; or it is possible that man was in fact just learning to use his eyes. During these years human beings discovered for the first time that the best way to learn the truth about their surroundings was by observation and experiment, rather than by revelation or by philosophical argument.

This period marked the third important appearance of the will to know. In the few centuries that have elapsed since the time of Copernicus the great driving force behind all human knowledge has caused the flame of scientific learning to burn with ever increasing brilliancy. The results of this most recent appearance of the will to know have been so numerous and so

important that few believe it is destined to follow the path of its two predecessors into the discard, although in comparison with the age of early religious belief in revelation or of the later Greek philosophy it is very young indeed. Certainly no one is prepared to suggest what the next development might be, if indeed there is to be one.

As soon as it was suspected that something was wrong with the mass of accepted scientific lore impounded in the twenty-century old writings of Aristotle the new epoch was at hand. And when at last, during the sixteenth and seventeenth centuries, it was recognized for the first time that supposed truths could actually be tested by experiment; that in the case of a disagreement between philosophical theory and experiment, the experimental fact was to be kept and the theory discarded; then the era of modern science was fairly under way. It had now become possible to question the accepted dogma and in some cases actually to disprove it. Others before Copernicus had discussed the possibility of a heliocentric solar system. One importance of the writings of Copernicus lies in the fact that their truth was so soon to be shown by the observations of Galileo.

The correctness of this new approach to knowledge may be judged by its results. Scientific knowledge, having remained stationary for some two thousand years, commenced to grow and has continued by leaps and bounds. Whereas a limit can be set to the duration of the artistic and literary Renaissance the scientific Renaissance is still at hand. Its continuing presence

goes to show that the great advances made in scientific knowledge have been a result of more than the general awakening in human thought. They attest the intrinsic soundness of the new experimental method. Men were at last learning to find out things for themselves.

In such an age da Gama could set out on his voyage of exploration, Columbus was able to obtain support for a journey that many believed would carry him over the edge of a flat earth, and Magellan had the faith to sail continually westward with the hope of thereby returning to his starting point. In such an age Harvey dared to proclaim his new observations concerning the continuous circulation of blood in the body. And in such an age Galileo hoped to prove by experiment that heavy and light objects all fall to the ground with the same acceleration, an idea that was expressly forbidden by the almost universally respected writings of Aristotle.

One of the most discussed features of the age was the fight against the development of the new idea by the organized church. It has since become evident that in so doing the church really acted against its own best interests. Believing as it did in the biblical cosmogony, it found the cosmogony of Aristotle peculiarly suited to its needs. The church therefore undertook to preserve the orthodoxy of Aristotle's scientific writings at all costs. Although the Greeks had placed the earth at the center of creation for different reasons than had the biblical cosmogonists, still both agreed that the earth was at the center, which for the church of the sixteenth and seventeenth cen-

turies was the important thing. By staking the truth of all religious faith on the scientific truth of every statement in the Bible the church stood in danger of losing, not only a few parts of supposedly revealed truth, but the whole.

Apparently it is as true now as ever that mankind demands the whole or nothing. Either a man must accept the entire dogma that is popular at the time or he is regarded as a heretic. It seems to be impossible for him to accept the good and true parts of several philosophies at once, which are not so often as is supposed mutually exclusive.

In the age of scientific awakening when human beings were learning to use their eyes, to observe, and to experiment, mankind took a bigger step upward than was then realized, either by the scientists and explorers themselves or by their antagonists, the organized church and those sluggish minds who still looked to Aristotle for all of scientific truth. No one at the time could foresee experimental science as we know it. While the church saw its God being forced still lower in the scale of significance, few realized the gain in significance of both God and man that was destined to follow the development of the new method of acquiring knowledge.

To an admirer of the Greek ideal of the perfection of the human mind, man must have been regarded at this time as having lost much while gaining little. In the Golden Age of Greece the mind had been raised to the exalted position where it was supposed to be able to discover all truths and mysteries without ap-

peal to anything outside of itself. Now it was apparently losing this ability. If the final appeal must be to objective experiment and not to philosophical thought, was not man assuming a position of great unimportance in the universe? If the men of his time could have foreseen the implications of Galileo's insistence on experiment as the source of scientific truth, how eagerly would they have flocked around him to become his disciples!

There is no need at present to do more than mention a few of the immediate successes of the experimental method, successes which soon showed that the loss of faith in the Greek ideal had not greatly decreased the power of the human mind to understand the universe and man's place therein.

Newton's discovery of the law of gravitation, as well as his formulation of the famous laws of motion, would not have been possible if Galileo's experiments had not already shown the falseness of the mechanical theories of Aristotle. The laws of Newton in turn together with principles of mathematics discovered later, and increasingly accurate astronomical observations, led to the triumphant mathematical discovery of the planet Neptune. The chemistry of Dalton, Lavoisier, and others could never have been developed without the extensive use of the chemical balance, which showed the falseness of older views concerning the fundamental units of matter. In the same way the modern steam engine is a result of experiments that overthrew old ideas, and the electric motor and dynamo, with all their uses in the modern world, fol-

low not from philosophy but from the experiments of Faraday.

In the meantime a line of discovery was being instigated in a new field which was to have the greatest importance in the evaluation of questions as to the significance, the aspirations, and the future of mankind. This movement was started when in 1831 the young student Charles Darwin, urged onward by the will to know, set out in the *Beagle* for a voyage of biological observation. The results of this voyage have had more repercussions in every line of thought and among men of every station in life than has any other piece of scientific work since the establishment of the Copernican theory by Galileo, Kepler, and Newton.

Many persons are acquainted with "The Origin of Species" either by hearsay or by reading abstracts from it as published in some outline of knowledge or in essays written by those who either agree or disagree with the hypothesis advanced by its author.

A lay reader perusing the book itself cannot help being dazzled by the immense accumulation of biological facts included in this great work, and is generally perplexed by the frequency of occurrence of technical names and enumerations of species and varieties of plants and animals. Such a reader will generally skip along until he finds a statement of Darwin's conclusion and will then agree or disagree, depending on how his prejudice prompts him, having disregarded the very facts on which the theory has been based. And when he comes to "The Descent of Man" he is

very likely, even now when evolution is not so unpopular as it was a few years ago, to throw up his hands in horror at what he thinks Darwin meant, not knowing in most cases exactly what Darwin did mean, not realizing that if it is true that "God created man in His image" He may very well have made use of a process much the same as that described by Darwin. It should be stated that few biologists of the present day accept this belief. It would seem sometimes that man is not content to have been created by God in His image, but must insist on creating God in man's image, even attributing to Him the shortsightedness which is and always has been characteristic of the human mind. If, as Darwin himself pointed out, one desires to see the handiwork of God, why look further than the changes and developments going on in nature, where new species are all the time appearing as if under the hand of a Creator who is still at work, still perhaps forming man more and more in His image, or perhaps developing man for some great purpose still unknown to us.

Again, as in the time of Copernicus and Galileo, the organized church stepped in with a renewed attempt to smother the will to know. Generally without trying to understand the new facts and hypotheses of science, religious leaders at once condemned the idea that man might have risen from the lower animals. The divinity of man has been and still is sacred to such men of religion; so it is to a great many scientists. The only difference is that the scientists face the future with open minds. The scientists may well ask: Why is man

the better for having been created all at once, instead of step by step? Man is a rather complicated piece of mechanism to have been created without at least a trial or two, even by an allpowerful Creator.

The will to know has survived in spite of the organized efforts that have been made to stifle it. Whether it exists as a mere accident or as some would like to believe as an everpresent force driving men forever onward to greater things, is a matter for personal opinion. Its very persistence is its most significant feature. Subjugated for centuries at a time it always manages to emerge at last, each time bringing with it a new period of development of knowledge and of human welfare. The opinion may be ventured that it will always be one of the most noteworthy features of human existence, forming a sharp line of demarcation between man and the remainder of the known universe.

"The Descent of Man" was published in 1871. In the sixty years and more since this book as well as the earlier "Origin of Species" appeared, Darwin's work has been the foundation of similar investigations. Whenever biological evolution is mentioned one is apt to find Darwin's name as well. Today evolution is a very popular word. Textbooks tell of the evolution of plants, animals, and man; the evolution of the solar system; the evolution even of the spiral nebulae and of the great system of nebulae and star clusters which is the universe. The layman has also adopted the word for his own, and will rarely pass by an article in one of the Sunday feature supplements bearing a

title which includes the magic word. But whether such a man thinks that the theories of Darwin and of the later biologists who have built upon his work have altered the meaning of human life for better or for worse is hard to tell.

Since the closing years of the last century the horizons of knowledge, under the pressure of the will to know, and by use of the increasingly powerful experimental method, have been widening at an ever increasing rate. Neither revelation nor Greek philosophy ever gave us anything like x-rays, radioactivity, or the quantum theory of radiation. Even Einstein's conception of our universe, one of the greatest philosophical conceptions of the present century, was brought forward as the result of an experiment, and has since been verified by many new experiments. And in biology Morgan's classic experiments with the fruit fly Drosophila melanogaster have renewed and strengthened the hope that sometime human beings will be able to mould the race into any pattern that may seem desirable. All these investigations have pushed back the boundaries of ignorance beyond the wildest dreams of our grandfathers, or even of our immediate parents. But still, as ever in the past, there are boundaries beyond which neither the eye nor the mind of man can discern anything with clarity.

What of the past? The existence of life on earth has been traced backward to a single cell of protoplasm floating in the waters of a primordial world. Whence came this cell? Was the existence of this ancestral cell a mere accident? And what of the future? The

characteristics of living things have been found to depend on the genes, minute parts of the cells from which plant, animal, or man is to grow. Can we ever hope so to alter a cell that we can with certainty produce a plant or animal according to previously drawn-up specifications and adaptable to special purposes? Is man undergoing change or development along any particular line, and if so what is this line and can it be controlled? Is the universe running down, and if so what hope can mankind have for the remote future? Is life destined to perish in all the universe? And finally, is there anything in nature that demands with the same insistence that the Michelson-Morley experiment demanded the hypotheses of Einstein's theory of relativity, the existence of a Creator, whether part of nature or above it? Can we discover any evidence that, as Millikan has said, the Creator is still on the job?

The answers to these questions are being sought today on many frontiers, with even more eagerness and often with as much peril as has been present on any frontier in the past. In the name of knowledge men are still facing death, whether in the form of mountain avalanches which threaten a party intent on the study of cosmic rays, or in the form of infection by dangerous disease germs; whether in the form of the crushing pressure of ocean depths or the lack of pressure at high altitudes. In spite of all dangers the work goes forward, and mankind cannot seem to resist it.

Where is all this work leading us? Is it true that

more knowledge will of necessity lead us to a better life, or, as some gloomy prophets maintain, will it lead man to his destruction? Given the means, is man fitted to control his destiny?

It is our purpose to visit each of the present frontiers of science, to see what is being done there, and to make inquiry as to the possible effect of this work on human destiny, and on man's idea of his place in a universe which at times appears to be so vast and so incomprehensible as to render the human race a thing of supreme insignificance.

Frontiers of Time and Space

CHAPTER II

WHAT THE TELESCOPE REVEALS

More exciting than a first telescopic view of the planet Saturn is the experience of turning a telescope to a region of the sky apparently containing few stars and seeing for the first time some of the myriads of stars that are really there.

Millions upon millions of stars are observable, of which merely a few thousands are visible to the unaided eye.

The sudden unfolding of the starry universe to an observer with a good telescope is a condensed history of many years of observation. Telescopes, each larger than the preceding, have continually pushed back the frontiers of time and space and forced mankind to revise earlier estimates of the magnitude of the heavens.

When Galileo first turned his telescope to the night sky, his mood was probably not unlike that of the modern who takes his first look through a descendant of Galileo's invention. And as he watched from night to night, as the conviction deepened that what he saw near Jupiter were in reality satellites not unlike the moon, and that the planet Venus actually showed phases as predicted by Copernicus, he may have felt something of what the present-day astronomer feels when he has measured the distance to one of the more

distant spiral nebulae and realizes its remoteness in distance and time.

Even after looking through a large telescope the layman is astonished when he sees, arranged row on row, the catalogs of stars and other celestial objects that have been studied and listed; the thousands of photographic plates, each appearing to contain countless images of stars, though these images have been counted, that are preserved in many observatories. These are a heritage of little more than three centuries. The few thousand stars that were observed and cataloged by Ptolemy and by Tycho Brahe are as nothing when compared to the immense number that are now known.

Let us imagine that one of the great telescopes has been put at our disposal for our first intimate glimpse of the heavens.

What shall we look at first? If the moon happens to be up it will surely receive our attention. We may not be entirely surprised at the mountain peaks and ranges, for we have often seen indistinct markings. We should not be astonished by the lack of twilight features, showing the absence of an atmosphere, for the sharpness of the edge of the new moon has long been familiar. We slip in an eyepiece of higher power and discover that the mountains are not greatly different from some that can be seen on earth, Vesuvius for example. There is no sign of water or vegetation. A little disappointed, we return to the low-power eyepiece and notice again the beauty of the shining golden crescent.

Over in the west, just above the treetops, is a bright

PLATE II
A cluster of stars.

object which according to our charts is the planet Venus.

Venus, in contrast to the moon, improves on acquaintance. With the low power she appears far more brilliant than to the unaided eye, and with the high power a veritable thing of beauty. If we are lucky we shall see her in crescent phase, as Galileo did when he wrote his famous anagram: The goddess of love imitates the phases of Cynthia. Truly this planet has been appropriately named.

Mercury, we are told, has already set. He is so near the sun that we cannot hope to see him except on rare occasions. Let him run his course. He is so small and so hot that his parched surface would not show us much of interest.

Overhead are two objects which the charts tell us are the planets Mars and Jupiter. Remembering Lowell's conviction that Mars is the abode of life, we hope to see for ourselves whether Lowell was right. The low power does not show us much. With the high power we see a ruddy disc with some very indistinct markings, blurred by the motion of air above the earth that at the same time causes the stars to twinkle. We watch for some time in an attempt to find a favorable moment, but even when it comes for a brief instant we can see little more than some greenish and brownish patches, crossed by faint markings that we would hesitate to describe. If conditions are especially good we may notice two satellites, Deimos and Phobos, which are close to the planet's surface. But we can hardly see any evidence of habitation.

Jupiter presents more of a spectacle. The low

power shows at once the four satellites made famous by Galileo's discovery. We choose the low power for our first examination because Galileo was limited to the rather small magnification of about thirty diameters. We have decided to look first as he looked, then to see what differences appear when the resources of modern instrument-making are brought to our aid. Even the low power gives us an immense advantage over Galileo, for his telescope had a small aperture, and his lenses were of inferior quality when judged by modern standards. With a larger aperture and more light-gathering power, an equivalent magnification will reveal more to our eyes than Galileo ever saw.

In the midst of the satellites is the great planet, the most massive member of the solar system except the sun itself, crossed by purple-brown stripes or bands which run parallel to the equator. Eagerly we reach for the high power eyepiece and slip it into the tube. Now we notice that the equatorial bands have distinguishable markings. There is the bay marking the site of the great red spot that once appeared, lasted for years in the same position, then gradually faded. Did this spot indicate the presence of a high mountain or extinct volcano, invisible to us through the dense cloud layer that covers the planet? Even as we look it is apparent that the planet has rotated slightly. We recall that Jupiter rotates upon its axis once in about ten hours, an observation which we could readily have made.

If our eyes are good we may see five more satellites,

some discovered very recently, making nine in all, a very respectable number of moons for one planet. Probably we shall be unable to see all nine as one or two are faint, and several may be in eclipse behind the huge planet.

Saturn is not so brilliant an object as Jupiter but we find him at last, shining among the stars with an orange light. The rings show up clearly, and the shadow of the rings is visible on the front side of the planet as well as the shadow of the planet on the rings behind. Several satellites can be identified, one casting a shadow looking like a small black dot on the planet's surface. As we watch we may see another moon coming out of eclipse from behind the ball of the planet. It is a magnificent spectacle, especially when the air is somewhat unsteady and the image shakes, giving Saturn the appearance of being in rapid rotation.

Probably it will be necessary to have Uranus pointed out to us, for this planet is hardly bright enough to be visible to the unaided eye except under the best conditions, and even then would not be an impressive object. Uranus was unknown to ancient observers, being discovered by Herschel when examining the sky with one of his great reflectors.

We ask that Neptune be found for us. He is even smaller and fainter than Uranus, of especial interest because of his remarkable discovery. It was indeed a triumph of the era of Newtonian mechanics when Adams and Leverrier each predicted the position of Neptune from a calculation of his disturbing gravita-

tional attraction on Uranus, and when the planet was found in the very position predicted.

A glance at Pluto, swimming in the outer darkness, completes our tour of the solar system. Faint and small, distinguishable from a faint star only by his motion, it is no wonder that his discovery was so long delayed.

If a comet were visible it would have been included in our list of observations. Many small planetary bodies, the asteroids, circulate between the orbits of Mars and Jupiter, but in our eagerness to look beyond the solar system we have passed them by.

Midnight has come and gone. We decide to follow the custom of many astronomers and descend from the dome for a cup of cocoa and a sandwich. When we return we wrap our coats a little more closely about us.

What shall we look at now? Stars are everywhere overhead, blue, red, and white, and the milky way extends in a long arc across the sky. Through the telescope the stars appear not as discs like the planets, but as brilliant points of light. Even the nearest star is so far away that the telescope, large as it is, is not large enough to show a sizable image. Sirius, the dog star, shines with a piercing blue-white gleam. Betelgeuse and Aldebaran are redder. As seen through the telescope the color of each star becomes more vivid than we had ever noticed.

Castor shows two brilliant points of light instead of one, close together, like a pair of jewels. We are told that it is a double star, the two components moving

around each other in orbits, each star attracted to the other. Soon we see other double stars, some of contrasting colors, red, yellow, blue, or white. Double stars are not so numerous as single ones, but they are by no means rare.

The richness of stars in the milky way is striking. The hazy white lane now appears as it really is, a huge cloud of stars, many, we are told, being far superior to our sun.

As the evening advances the stars move ever westward, followed by the faithful guiding clock of the telescope. A faint hazy patch claims our attention. We direct the tube and see the Andromeda nebula, oval-shaped, appearing like a great mass of shining vapor, brightest at the center. It is different from the great irregular nebula that can be seen when examining the stars in Orion's belt, and more symmetrical. Another hazy patch turns out to be a loose cluster of stars, and yet another a dense globular cluster.

As a climax to the evening a planetary nebula is shown to us. It is so faint that we, astronomical laymen, might never have found it. Small and more or less round, it is a beautiful sight: a globe of bluish vapor containing at the center a yellow star. As we descend, a trifle wearily, from the dome and see again the whole starry sky as we have seen it so often, there is a new meaning in the heavens of which we have been privileged to see a little more than we had hoped.

For modern astronomy, especially that branch which deals with remote or faint objects, the human eye is not a very good instrument, and the photo-

graphic plate has displaced it to a large extent. Many nebulae, for example, are so faint that were it not for the ability of the plate to store up light-impressions during long exposures, they would not be known. This quality of the photographic plate is also indispensable in showing the faint details of such objects as the Andromeda nebula. The spiral structure of this and many similar nebulae is hardly apparent to the eye but is plainly recorded on plates which have been continuously exposed, sometimes for hours. Placed at the focus of a modern telescope, the plate records clearly and permanently the details of faint nebulae, star clusters, and groups of celestial bodies. An observer at the eyepiece could never hope to see a nebula so clearly or in such great detail as is shown in the accompanying photographs.

Gradually, as man's acquaintance with the stars has widened, has his knowledge concerning the sizes, distances, and physical conditions of these celestial objects increased.

The first actual measurement of the semiannual parallax* of a star was important, not only in giving the distance to the star, but in showing indubitably that Copernicus had been correct. The effect of stellar parallax had indeed been demanded of him by his opponents; for if, as was then erroneously supposed, the stars were all of the same intrinsic brightness, appearing of different stellar magnitudes only because of their different distances from the earth, the postu-

* Parallax is the apparent motion or displacement of an object caused by a motion of the observer.

PLATE III

Jupiter and four of his satellites.

lated motion of the earth around the sun should alter to some extent the relative positions of the stars as seen from the moving earth.

Any traveler is familiar with the illusion that distant objects appear to share in the motion of the train, while nearer objects seem to move backward. The apparent relative motion is more pronounced when the objects are quite widely separated, one being in the foreground and the other in the distance. Two adjacent objects at the same distance from the train have no such parallactic motion as the train moves forward. They appear to move backward as the train advances, keeping their position with respect to each other as viewed from the train. The same is nearly true of all very remote objects, which appear to have no appreciable relative motion, even though one is more distant than the other, unless the observer watches for a long time and notices the relative displacement. The relative velocities as seen from the train would not in this case be appreciably different.

If the semiannual parallax of the stars had been larger it would have been observed earlier. For years the only way of measuring the distance to a star, this method of celestial triangulation with the diameter of the earth's orbit as a baseline is now the first step in more complicated modern methods of estimating stellar distance. At best only a few thousand stars are sufficiently near to show a semiannual parallactic displacement.

What the astronomer actually observes is the displacement, not the motion, but the amount of the semi-

annual displacement is limited by the size of the earth's orbit, and by the fact that the earth returns periodically to its original position in the orbit. The parallactic motion of the stars due to the actual motion in space of the entire solar system depends on a knowledge of the sun's motion, in both direction and amount. Parallactic motion or displacement from this cause will give large displacements in time, but the time is generally large.

The distances of many stars too remote to show a parallactic displacement are known, and by several clever subterfuges. Such methods depend on a knowledge of the characteristics of variable stars, so that these variables have aptly been called the yardsticks of the universe.

A variable star is one that changes in brightness. There are several types of variables. The simplest is the Algol type, named after Algol, a double star whose orbit is so oriented that each component periodically eclipses the other. A study of the variation of the light from such a star gives the relative brightness of each component and the period of rotation, as well as other information about the orbit. More useful for purposes of cosmic sounding are the so-called Cepheid variables, named after δ-Cephei, the first star of this type to be observed, and the irregular variables. Each type has a characteristic curve of light variation.

It has been found from a study of such variables as are sufficiently close to permit direct determination of their distance, and hence their intrinsic brightness, that for the Cepheids and the irregular variables a

definite relation exists between the period of light variation and the intrinsic brightness of the star. With the assumption that this relation exists for all variables of the same type, however distant from us, an assumption that is as safe to make as many assumptions based on empirical laws that are made in all the sciences, the usefulness of the variables as measurers of distance becomes apparent: Given the period of such a star observed in a remote nebula or star cloud, then the intrinsic brightness, luminosity, or so-called absolute magnitude becomes at once a known quantity. The simple measurement of the apparent average brightness of the particular star then gives the distance of the star, and at the same time the distance of other stars in the nebula or cloud. Other physical conditions can then be determined for the stars in the group, whose distance is now known.

Less dependable methods of determining stellar distances are used when better methods fail. For example, the distances of the very remote spiral nebulae, in which individual stars cannot be distinguished, must be estimated from their apparent size or brightness, together with certain assumptions based on a knowledge of nearer objects of the same sort in which variable stars have been observed.

Comparatively recent developments in the application of physical methods, especially spectroscopy, to the study of astronomical bodies, incorporated in the science of astrophysics, have greatly extended our knowledge of the structure and scale of the siderial universe. We proceed to a discussion of this new and powerful science.

CHAPTER III

ASTROPHYSICS

When in the middle of the last century Kirchhoff and Bunsen began their spectroscopic examination of the chemical elements they may be said, in the vulgar phrase of the day, to have started something. An extension of their work has led to a knowledge of stellar evolution.

The early days of spectroscopy were distinguished by simple optical arrangements and crude theoretical knowledge. Then it was a matter of arranging a lens and prism adjacent to a Bunsen flame in which was introduced sodium chloride, potassium nitrate, or what not. At first colored drawings of the spectra would be made, and later the wavelengths of each spectrum image, or spectrum line, would be measured and cataloged. The analytical chemist was thus enabled to repeat the process with his unknown sample, observe the spectrum lines, then look up each one in his catalog in order to identify the elements present in his sample.

The science of spectroscopy could then claim very little help from theory. When, as was inevitable, the spectroscope was first used as an adjunct to the astronomical telescope, only a few of the multitude of spectrum lines from sun or star could be identified, and speculation was rife as to the possible existence

of new or unknown elements in the celestial bodies. Helium indeed was discovered on earth after the name had been given to an element assumed to be responsible for certain lines in the solar spectrum.

The present state of spectroscopy is quite different. Not only have powerful instruments been placed at the disposal of scientists, but a complete and comprehensive theory has been developed, aiding in the identification of spectrum lines of unknown origin, and tying up the observations of spectroscopy with atomic structure. This theory will be discussed in future chapters. At present it is more interesting to examine the astronomical discoveries that have resulted from the adoption of this new science.

The spectra of stars differ widely among themselves, but most of them have one characteristic in common: Each consists of a band of color, ranging in the usual sequence from red to violet, crossed at intervals by dark lines. It is these dark lines that are of the greatest interest to astronomers.

An incandescent solid, such as a tungsten lamp filament or a glowing iron poker, gives a continuous spectrum including the well-known rainbow colors. A sodium flame, the yellow flame obtained by putting common salt in a gas or candle flame, gives in the visible spectrum two fine lines very close together. But a glowing lamp filament, when seen through the sodium flame, produces a continuous spectrum crossed by two fine black lines, close together, in exactly the part of the spectrum formerly occupied by the yellow sodium lines. Sodium vapor absorbs light of exactly

the wavelength it would emit if heated or if excited to radiate by passing an electric spark through the vapor. Since the filament is hotter than the sodium flame, the sodium lines appear dark on a bright background.

In the same way is explained the observed absorption in stellar spectra. The laboratory experiment thus demonstrates what is happening in remote space. The dense central portion of a star acts like an incandescent solid, giving a continuous spectrum, while the cooler, tenuous outer regions of the stellar atmosphere produce the observed absorption.

A very few stars, however, do show bright lines in their spectra, which can only mean that the outer atmospheres of such stars are very hot.

Certain nebulae, now known to be rare and gaseous, produce only bright spectrum lines, characteristic of gaseous material. This observation forms a crucial test and was in certain cases the first clear indication of the nebular character of these objects. A faint star cluster or a nebula containing stars, such as the Andromeda nebula, always shows the continuous background characteristic of the spectrum of a star. Modern instruments show many stars in the Andromeda nebula, but there are many nebulae in remote space in which no separate stars can be distinguished. In such cases the spectroscope is indispensable and its word is final.

Some stars are red, others blue-white, and these differences in color are apparent when the stars are examined spectroscopically. The spectrum of a red

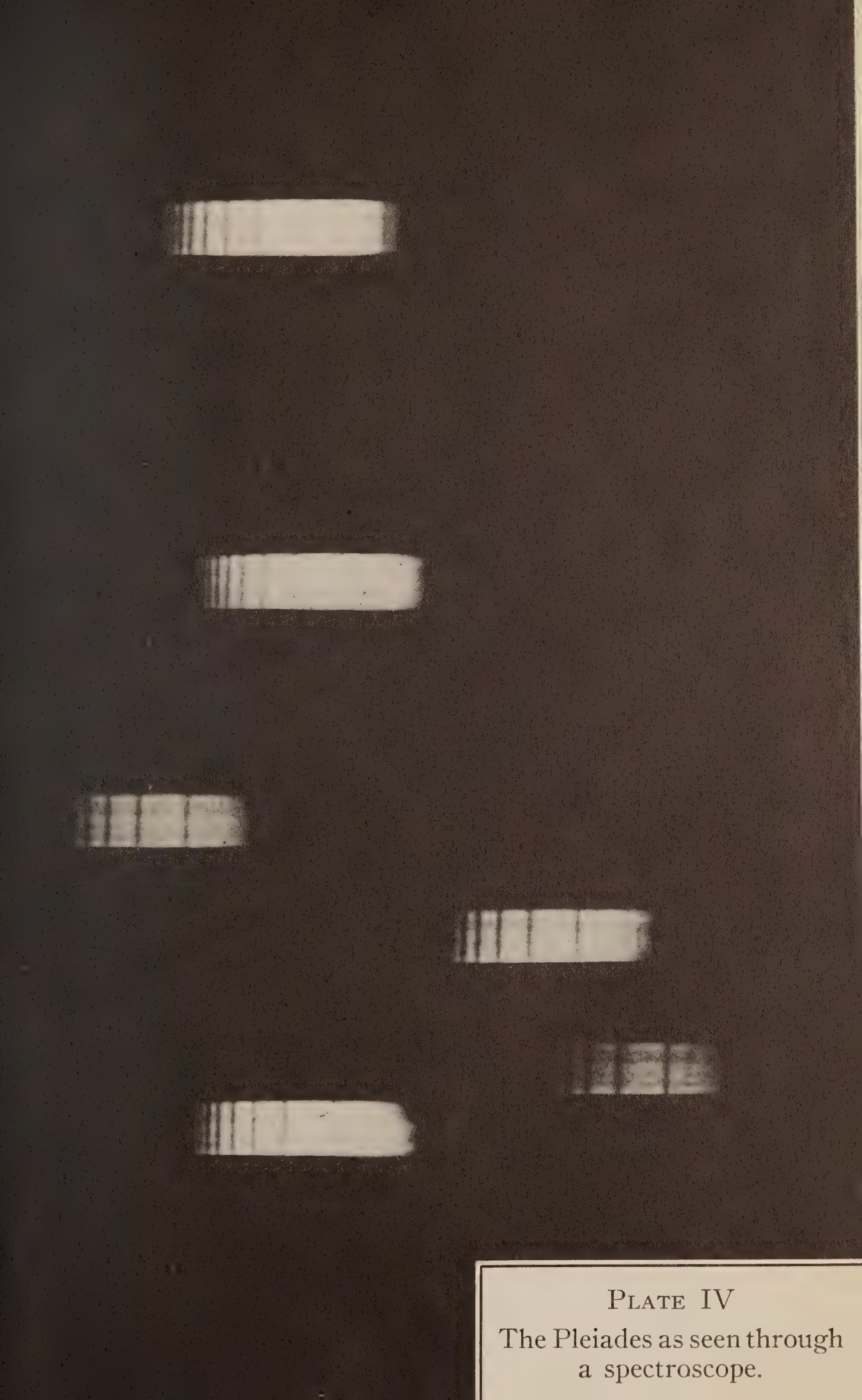


PLATE IV

The Pleiades as seen through a spectroscope.

star extends farther to the red and not so far to the blue end of the spectrum as that of a white or blue star.

Stars have been classified in many ways. First arose the idea of magnitude, or apparent brightness. Early astronomers divided all visible stars into five magnitudes, those of the first magnitude being the brightest. Modern astronomy has taken over the system with some modification; the more exact modern classification, based on photometric measurements, includes stars of the zero and minus-one magnitude, while on the same scale the sun, very much brighter than stars of the first magnitude, has a magnitude of minus twenty-seven.

When the photographic plate came into wide use, the color-index of a star was added to the list of classifications. The ordinary photographic plate is most sensitive in the blue region of the spectrum, while the eye is most sensitive in the yellow-green, exactly the region where the sun's radiation is the most intense. Accordingly a photograph of a familiar constellation taken on an ordinary plate will not show the stars in the same relative brightness as is seen with the eye. The color index is the difference of the photographic and the visual magnitude, and expresses the redness or blueness of a star.

A preliminary attempt at stellar classification according to color and perhaps something more has been made by Secchi, and we hear of Secchi's types of stars. These types are four in number, ranging from blue stars to red stars, or as was believed at the time,

from early type stars to late type stars, the adjectives denoting position in the evolutionary life of a star. The blue-white stars were supposed to be hotter than the red ones, in analogy to the behavior of a heated poker, which becomes first red, then white-hot, as its temperature is raised. Stars were supposed to exist originally at a high temperature and cool gradually, finally becoming extinct. The spectrum of a star of Secchi's first type extends farther in the blue and not so far in the red end of the spectrum as a star of a later type. Moreover, the complexity and nature of the spectra in each type, when compared to similar spectra obtained in the laboratory under different conditions of temperature, pressure, and energy of excitation of the luminous source gives conclusive evidence of the correctness of the view that the temperature decreases from Secchi's first to his fourth type of star.

As spectroscopic knowledge increased it became clear that four types were not adequate to express the many variations in the spectra of stars. Other classifications arose, of which the so-called Harvard classification has been agreed upon by astronomers the world over. It is based to some extent on Secchi's earlier classification.

According to the Harvard classification, stars are classed under the types, in order: *B, A, F, G, K, M,* and so on. The order was originally intended to be alphabetical but was altered when more was learned about the line of evolution of a typical star. Under each letter there are ten subtypes. We may read of

a star of class $F3$, or $G0$, which latter happens to be the type of our sun. Occasionally additional subscripts are added, such as *e* to denote the presence of bright or emission lines, as contrasted to the more usual absorption lines, in the stellar spectrum.

The most complete catalog of spectral types, the Henry Draper catalog, has been made at the Harvard observatory by Miss Cannon. In preparing this catalog the spectra of many stars, sometimes thousands, are all photographed on a single plate by placing a prism in front of the telescope, above the object glass, so that every star in the field appears as a spectrum. The stellar types are then classified by examining each spectrum image in turn with a small magnifying glass. After some practice the ability to recognize a spectrum as belonging, say, to class $B3$ comes as easily as the ability to recognize a neighbor.

The Harvard classification has been useful in helping to straighten out the order of stellar evolution. A discussion of this subject must be left until later in the chapter. The statement of the type of a star, with an added name that will soon be mentioned, at once places the star as an early or a late star, referring again to its place in the evolutionary scheme.

The Doppler effect was originally discovered for the case of sound waves, but later applied to light it has been of the greatest service to astronomers. Everyone is familiar with it. Who has not noticed a drop in the pitch of a crossing bell as the train in which he is riding passes, or a change in the note of the train whistle if the observer happens to be

standing on the station platform? The explanation is almost as simple as the observation: If source and observer are approaching each other, the number of waves per second reaching the observer is increased and the apparent wavelength is shortened, while if source and observer are receding from each other the converse is true. Light from a star will appear to be bluer or redder as observer and star are approaching or receding, and the shift in wavelength and consequently the relative velocity of source and observer will be measurable by changes in the positions of spectrum lines.

In the case of sound waves, whose velocity is comparable to velocities which can be attained by trains and automobiles, the shift in frequency or pitch can easily be noticed by the unaided ear. But the velocity of light is so much greater than any velocity attainable by train, airplane, rifle bullet, or even the high velocities of most of the spiral nebulae, that the eye alone would never be able to detect the minute change in light color resulting from a relative motion of source and observer. A spectroscope is required. This instrument is able to measure the frequency, or wavelength, of light with great accuracy and can detect a change in frequency of light corresponding to very moderate relative velocities.

Spectroscopic application of the Doppler effect has long been used in astronomy in studying the radial velocities of celestial objects, the velocity in the line of sight, toward or away from the earth. No other direct method will give this particular information.

The effect has also been useful in discovering and identifying a particular class of double stars, the so-called spectroscopic binaries. These stars were discovered when it was found that the spectrum lines of certain stars were sometimes sharp and sometimes broad and diffuse, occasionally even becoming double. The explanation was not far to seek: what was being observed must be a binary star, too distant or too narrowly separated to appear in the telescope as a binary. As the stars rotate about their center of gravity each alternately approaches the earth and recedes from it, and the spectrum lines of each are seen alternately to shift toward the blue and then the red end of the spectrum. When the stars are in line with each other and with the earth the spectrum lines are sharp, for in this condition the two spectra become superposed. If an eclipse occurred the binary nature of the star would already be known from the light curve, as mentioned above. During the eclipse the spectrum would be entirely or principally from the star eclipsing the other. From a study of the changing spectrum of a spectroscopic binary many things about the star and each of its components can be found. For an eclipsing binary, the light curve and the periodic change in the spectra of the stars are in complete agreement as to the nature of the object.

The Cepheid variables mentioned above have not as yet yielded to any such simple explanation. Although there is a definite relation between the light curve and the periodic change in the spectrum, in this case a change in relative intensity of the lines as well as

the Doppler shift, the relation is of such a sort as to denote something like expansion of the star as a whole, together with changes in temperature and physical condition at the star's surface. But the incomplete knowledge of the mechanism of variation of the Cepheids does not prevent their use as yardsticks of the universe.

In connection with still another method of stellar classification the spectroscope has been useful in determining the scale of the universe. Although fairly comparable to each other in mass, stars are of widely differing sizes. The size of the sun is directly measurable. The diameters of most other stars are obtained in a more indirect manner. For as has been mentioned, even the nearest of our neighboring stars appear as points in the largest of modern telescopes, not as perceptible discs as is the case with the planets.

It has been noted that in the case of eclipsing binary stars the form of the light curve gives among other information a knowledge of the relative diameters of the two components. For other stars a less direct method must be used.

From a knowledge of the surface temperature of each star obtained in a manner to be explained below, the color index, and the distance, the diameter can be deduced by means of reasonable assumptions as to the density of each star and the mass found. The method depends on theoretical reasoning from the temperature, intrinsic brightness or absolute magnitude, and spectral type, making use of the laws of black body radiation which are to be explained in a future chapter.

From such studies has arisen the classification of stars according to size as giants or dwarfs.

It must not be supposed that giant stars are the brightest stars in the sky, or dwarfs the faintest. The apparent brightness of a star, or its magnitude, depends on intrinsic brightness, size, and distance from the earth. Giants and dwarfs are respectively stars of large or small diameter, referred of course to the average diameter of stars. As will be seen when stellar evolution is discussed, the sun is getting along toward the dwarf stage; for some purposes it can be called a dwarf.

To show that the somewhat indirect astronomical method of estimating the size of a star is not as unreliable as might be supposed, the diameter of Betelgeuse, a red star in the constellation Orion, estimated by such methods to be a giant of immense diameter, was measured at Mt. Wilson by Michelson, assisted by Anderson and Pease, with an immense stellar interferometer attached to the hundred-inch telescope. This instrument in effect widened the aperture of the telescope to such an extent that the actual diameter of the star could be detected. This interferometer would be more widely used if it were not such a cumbersome instrument. Astronomers were gratified when the direct measurement of the diameter of Betelgeuse came out some three hundred times as large as that of the sun, quite in agreement with their former estimates.

For stars that are fairly near to the sun and whose distances can be measured by trigonometric methods, the classification of stars as giants and dwarfs is quite

easy and definite. Not so with those stars that are too remote for their distances to be measured directly, or that are not members of star clouds or nebulae containing the invaluable variable stars, the yardsticks of the universe. But as has so often happened, the spectroscope has saved the day. It has been discovered that the spectra of giants and dwarfs, even though of the same spectral type according to the Harvard scheme, yet have characteristic differences which serve to distinguish them. Certain of the spectral lines are of different intensity in each case. Those who are familiar with spectra of the various types have learned to recognize a star as a giant or a dwarf from an examination of its spectrum alone. This familiarity acquired from stars that are our neighbors, so to speak, can be extended almost indefinitely, as far as the telescope can reach to pick up enough star light to register on the plate of the spectroscope. Then, knowing the classification of the star as a giant or dwarf, and its temperature, its absolute magnitude can be computed with fair accuracy, and from its apparent magnitude its distance can be determined.

The method of finding the distance of stars in the manner just described is known as the method of spectroscopic parallax. The title is perhaps a paradox, for no parallax is observed. Astronomers first measured distance by means of parallax, and they still speak of distance and parallax interchangeably. They have even defined an astronomical unit of distance, the parsec, which is the distance to a star that would have a parallax of one second of arc. One parsec is

equal to 3.26 light-years. It may be mentioned that the absolute magnitude, referred to above as a measure of the intrinsic brightness of a star, is defined as the apparent magnitude of the star if placed at a standard distance of ten parsecs.

Much has been said above concerning the temperatures of stars. It may seem surprising that these temperatures are obtained by the use of an instrument not unlike an ordinary thermometer. But there are several steps between the reading of the instrument and the knowledge of the star's temperature.

What is really used is a thermocouple. A thermocouple is simply a junction of metal wires of different materials. When this couple is connected to a galvanometer and the junction of the metals is heated, a current is produced which is observed by a deflection of a galvanometer. Actually there are two junctions, and only one is heated while the other is kept cool. By interchanging the hot and cold junctions a deflection in the opposite direction is obtained, thereby increasing the sensitivity of the instrument by obtaining a double deflection, a procedure which is useful in astronomical work in view of the extremely small amounts of heat that are available for study. Small metal discs called receivers are mounted at each junction. Thermocouples used in astronomical work are very delicately made, the entire sensitive part of the instrument often being much smaller than the wing of a mosquito. This part is mounted in a vacuum to avoid losses of heat by convection, while conduction losses are avoided by the delicate construc-

tion of the instrument, and the fine wires used. The instrument is placed at the focus of a telescope so that the image of planet or star can fall upon the receiver. The heat of the image then raises the temperature of the junction and the galvanometer deflects.

In order to translate galvanometer deflections into temperatures, a knowledge of the laws of radiation is necessary. These laws are obtained from laboratory experiments performed with bodies called black bodies, or perfect radiators.

A black body, being a perfect absorber when cool, becomes a perfect radiator when heated. Actually a hollow space contained within a heating coil is used, the radiation escaping from the furnace through a small hole. Radiation inside the space is in equilibrium at the temperature of the furnace, and the radiation has all the properties of the radiation from a black body at the corresponding temperature. More will be said about black bodies in a future chapter.

For each temperature there is a characteristic curve relating intensity of radiation with color, or wave-length. It is such curves that are used in interpreting the results of astronomical measurements with the thermocouple. One has only to assume that the star or planet is a perfect radiator so that the radiation emitted does not depend on the nature of the emitting surface, an assumption that is well justified because it cannot be far wrong in its results and no other equally logical assumption is possible, in order to interpret thermocouple readings in terms of the temperature of the emitting source.

Naturally such a method works only for the surface of a star, for we cannot see very far down into the star's material. Internal temperatures of stars must be derived from theoretical treatment, involving measured quantities such as the star's mass, size, luminosity, surface temperature, and so on. The results of such a theory are judged by the agreement with observation of observable deductions made from the theory.

What then of the evolution of a star? Before passing to the triumph of modern astrophysics it is necessary to discuss the scientific contribution that has made this knowledge definite.

Russell, the American astronomer, has likened the problem of stellar evolution to that of discovering from a short stroll through the forest the method of growth of a tree. In the sky there are stars of great variety and it is safe to assume that those we see are in various stages of their life history. If some method of classifying them all in a consistent scheme could be found, perhaps the scheme would indicate something of their line of development. As a result of his attempt there exists the Russell diagram.

Across the top of the diagram is a scale of spectral types according to the Harvard classification. Down the side is a scale of absolute magnitudes, the magnitudes that the stars would have if reduced to a standard distance of ten parsecs. Each star is placed on the diagram in its appropriate position.

There are two principal trends in the arrangement of the stars: One nearly horizontal across the top,

and one sloping downward and from left to right. This latter line is called the main sequence.

Let us see what this diagram can tell us about the evolution of a star.

According to older ideas of stellar evolution every star commenced as a luminous hot globe and cooled down, shrinking as its evolution proceeded, passing from a white-hot body through yellow and red heat to faintness, extinction, and death. This view was in some respects satisfying, except for the fact that it left one very pertinent question unsolved: How did the hot mass of gas get there in the beginning and why was it so hot? The modern theory eliminates the second part of the question.

Let us suppose that somewhere in space there exists a cool, diffuse, mass of material, gas molecules or dust. What will happen to it if left undisturbed? Every part will attract every other part by Newtonian gravitation, and the mass will condense. In the condensation work is done, for material particles have been acted upon by a force and have been moved. As the process continues, potential energy of position has been transformed into heat energy, and the mass gains in heat energy and soon begins to glow. Already its size is less than when it started but it is still huge. It is a red giant, and takes its place in the upper right hand part of the Russell diagram.

The normal star will not stop here, but will continue to shrink and to grow hotter. Accordingly it moves from right to left across the top of the diagram, shrinking all the while and growing hotter.

When it has reached the upper left of the diagram it has been raised to white heat, and while not so large as a red giant, is still impressive enough to merit the name, white giant.

It should be remembered that no one has seen, or hopes to see, a given star change in any such way. From the variety and the characteristics of many stars and the regularity of their arrangement in the Russell diagram it is inferred that if the lifetime of the observer were not so infinitesimally short this is what he would see, just as the man in the forest infers that large trees result from the growth of smaller ones.

The star has now run the gamut of color or spectral type and is as hot as it can get. It proceeds to cool, loss of heat by radiation now becoming greater than gain in heat energy by shrinkage. It starts down along the main sequence, becoming fainter all the while, and redder. About half way down it is similar to our sun. Steadily it descends the scale toward dwarfdom, passing again but in reverse order through the range of spectral types.

Such is the line of evolution of a typical star. But it is clear that the entire story has not been told. What of double stars, of star clusters, and of the greater organizations, the star clouds and spiral nebulae? And what of the assumption of the independent presence of so many cool globes of gaseous material, distributed throughout the universe, waiting for the chance to form stars?

In explaining the galaxy, the best that the cosmogonist can do is to start with a much larger, more ex-

tended mass of cool gaseous material than was needed to form a star. The origin of this material is at present the concern of religion or metaphysics, not of astronomy. However it came to be, it will condense under the mutual attraction of its various parts, and it may start rotation. For the random motion of each molecule or molecular group may not add up in such a way as to balance every rotational tendency. Any tendency to rotate would be accentuated as the mass shrank. With shrinkage the shape of the mass changes from irregular to something resembling a globe. It then becomes ellipsoidal, and finally parts of it may be thrown off. Each of these in turn continues to shrink, to rotate faster and faster and finally to divide, this time to form the separate stars or star clusters.

Much of the work in this field has been done by the astronomer Jeans, who investigated what would happen to a diffuse mass of gas in space, subject to the law of gravitation and the other well-known laws of physics and mechanics. The theory predicted the formation of certain shapes at different points along the evolutionary path, shapes which are duplicated by celestial objects well known to astronomers. This resemblance is rightly considered to indicate the truth of the theory.

A star may, instead of following the path laid down for it by the Russell diagram, do something out of the ordinary. For example, it may decide to become twins. Whether this happens depends on the state of rotation of the star. If this rotation is too rapid

the split will occur and then two stars instead of one pursue the evolutionary path, not necessarily with the same speed or in the same way. Of the many double stars known, few have components that are exactly alike, either in size or in color. More often the components are strikingly different, one being yellow and the other blue, one being dark and the other bright, or in the extreme case, like that of Sirius, one being a bright, wholly respectable star, and one being that celestial freak, a white dwarf, containing material so dense that every cubic inch weighs a ton.

CHAPTER IV

RELATIVITY

THE theories of Einstein are no longer the popular rage that they once were. The scientific layman has apparently discarded the theory of relativity and has become concerned, in imagination at least, with the smashing of atoms. Tomorrow he will no doubt be just as concerned about something else.

The daily papers print vivid accounts of the latest scientific discoveries, generally announced only tentatively by the scientists who are responsible, which are read at first with amazement, and later perhaps with amusement as still more recent discoveries become contradictory. Meanwhile scientific work goes quietly on, in study, seminar room, or laboratory, each man adding his bit to the structure that may sometime, though no scientist would venture to predict when, become a completed edifice.

Relativity is more than a scientific theory, it is a new philosophy; its implications are metaphysical as well as astronomical and physical. The scientific theory has arisen as a result of studying the mathematical, physical, and astronomical results of an idea distinctly philosophical in nature.

If the name of Einstein is more often associated with the theory than that of any other man, it is not

because the theory in its entirety has been his work. The idea was not foreign to metaphysics before his time. In the development of the mathematical theory the names of Minkowski, Eddington, Weyl, de Sitter, Tolman, Lemaître, and many others come to mind; of Sommerfeld and Dirac, who applied the theory to spectra and atomic structure. But it was Einstein who first showed the scientific and mathematical implications of the metaphysical conception.

From the time of Newton down to the present generation scientists have considered it legitimate to make two general assumptions: The first of these is the assumption of the uniformity of nature, that scientific truths discovered on earth or in that part of the universe immediately surrounding it can be regarded as applicable throughout all space and all time, and especially that these truths will hold as accurately in the outermost depths of space and in the small world of atomic dimensions as in the ordinary world directly available to human senses. The second assumption is that time must be an absolute and fundamental thing, flowing uniformly from the most distant past to the most remote future, the same for all observers, whether on earth, on a spiral nebula that appears to be receding with tremendous velocity, or in an atom.

Newton observed the fall of objects, including apples, to the earth and found by calculations based on astronomical observation that the moon, in order to remain in its orbit, must fall toward the earth according to the very law governing falling bodies near

the earth's surface. When he included the motion of apples and moon in his laws of motion, and when he formulated his famous law of universal gravitation which appeared to explain both, he had arrived as he thought at a bit of absolute truth. Every body in the universe, he said, attracted every other body with a force which was directly proportional to the product of the masses of the bodies and was inversely proportional to the square of the distance between them. Experimental facts were in agreement with the law, and the law was accepted. Thenceforth it was agreed that the law held accurately, not only within the solar system, but between stars and nebulae, even in those parts of the universe so remote that the most powerful telescopes were unable to reach them. The law was also supposed to be applicable to atoms and molecules.

The assumption of the universal applicability of scientific generalizations based on terrestrial measurements has been of the greatest use to science, and was perhaps a natural assumption to make. Science has for its aim the discovery of truth as well as a knowledge of the constitution and behavior of the universe in its entirety and in all its parts. Whether the above assumption has justification or not would seem to have been an open question; the desires of early scientists closed it and it has remained closed ever since, until very recent years. It was much more satisfying to be able to say, This law holds everywhere, it is a universal law of nature; than to be forced to admit that knowledge of remote regions is

as yet unattainable and must wait till measurements may be made directly on such remote regions, measurements which in fact may never be possible. To a scientist of Newton's day an admission that the question might still be open would have been an admission of defeat. It is not considered so today.

Can physics ever determine absolute and ultimate reality? Newton would probably have answered in the affirmative, as would many of his followers. Today, thanks principally to Einstein, science replies, We don't know. And in the admission that physical science may not be the path to intimate knowledge of the entire world, meaning of course the entire universe, scientists consider that they see a distinct advance.

The acceptance of the new point of view is anything but an admission of defeat. It is simply a turning of a new leaf, a determination not to be dogmatic about things concerning which science has realized it has no true knowledge. For true knowledge, in the scientific sense, has come to be synonymous with experimental knowledge. As will be seen, the belief that scientific generalization could be extended throughout all space and time has more than once led science up a blind alley. Scientists have learned to be more cautious.

Recently science has been limited to regions that are directly observable, regions in which experiments can be performed and observations made. This limitation has led to tremendous advances, and to a more secure faith in the truth of physical theory.

Let us see how the ideas contained in the theory of relativity have arisen.

A certain simple sort of relativity was inherent in Newton's work. It was also implied in the earlier experimental and mathematical work of Galileo, on which much of Newton's mechanics was based, and is called Galilean relativity.

Newton's first law of motion, the so-called law of inertia, informs us that every body at rest or in uniform motion in a straight line will continue in its state of rest or uniform motion unless some force compels the body to alter its state. The tendency of a body to remain at rest or in uniform rectilinear motion unless disturbed by a force is called inertia, and it is this inertia of a body that must be overcome when a heavy body at rest is to be set in motion, or accelerated. A coordinate system or a space described by such a system, in which the law of inertia is obeyed, is called an inertial system.

It can easily be seen that a great many separate inertial systems are possible. In particular, if we consider only the usual form of rectangular system, in which the coordinates defining the position of a point are x, y, z, then the uniform rectilinear motion of a body can as well be described with reference to any one of many such systems, all in uniform rectilinear motion with respect to a system at rest or with respect to each other, and oriented in any direction; the law of inertia will be true in each system. Any such system is as good as any other one for describing the uniform rectilinear motion of a body, and if a law

of physics holds in one of the systems it will hold in all of them. This is the principle of Galilean relativity. It is assumed that the relative velocities of the various systems are all considerably smaller than the velocity of light. Further, none of the systems may be accelerated, and no forces are allowed to be present.

The principle of Galilean relativity can thus be summed up in the statement that the laws of physics preserve their simple form when transformed from one inertial system to another; that is, that these laws hold equally well in all such systems. It is impossible by means of mechanical experiments performed within an inertial system to decide whether the system is at rest or in uniform rectilinear motion, or indeed what might be the direction of the motion, or its magnitude. The principle is somewhat similar to Einstein's restricted or special principle of relativity. Einstein announced this theory in 1905. But first came the now famous Michelson-Morley experiment.

This experiment, first performed shortly after 1880, had for its object the measurement of the earth's velocity through the ether. But what is the ether?

The ether is one of the many human inventions that have at times appeared necessary in order to explain scientific results. It was first postulated as the medium in which light waves were propagated from place to place, for in order to exist and travel from place to place a wave motion requires an elastic medium. The hypothetical ether had very strange properties. For example, it had to resemble an elastic

solid, and at the same time be so tenuous that the motion of the planets through it should not be retarded.

Additional reasons for belief in the existence of the ether arose from Faraday's work with induced electric charges and with electromagnetic induction in general. This imaginary medium was considered to be the seat of electric and magnetic forces. These forces could at the time be "explained" in no other way. Maxwell's later theory of the electromagnetic field, together with his prediction of electromagnetic waves whose velocity turned out to be equal to the velocity of light, gave additional credence to the ether theory.

In spite of the various scientific reasons for assuming the existence of the ether, difficulties remained, notably the one mentioned above. There was the added difficulty of forming a mental picture of the ether, cluttered as it was by the multitude of electric and magnetic forces, light waves, and what not, that were supposed to exist in it. The ether theory was becoming top-heavy.

The Michelson-Morley experiment was designed to measure the velocity of the earth with respect to the ether. Its failure to do so has resulted in the theory of relativity.

The classic analogy to this experiment is that of a man swimming a river. Very simple mathematical reasoning leads to the result that the swimmer can swim across stream a distance of say a hundred yards and back in less time than he can swim upstream the same distance and back to his starting point. In the

first case he will be forced to head somewhat upstream, and swims a distance rather longer than the direct distance of 100 yards across; the same is true of his return journey if he desires to return to the point on the shore from which he started. In the second case the actual distance covered is exactly twice 100 yards but the retarding effect of the current on the upward journey more than counteracts the helping action of the current when he swims downstream, so that the journey up and down takes longer than the journey across.

A more perfect analogy to the Michelson-Morley experiment is an experiment that can be performed with sound waves in a wind-tunnel. It would take sound less time to travel across the tunnel and be reflected back to its starting point than to travel an equal distance in the direction of the wind and back again.

In these analogies the moving stream of water or air takes the place of the supposed ether wind caused by the motion of the earth through space. The swimmer or the moving sound signal takes the place of the light signal.

Michelson and Morley designed an apparatus whereby two beams of light from a single source were separated and caused to travel an equal distance in two mutually perpendicular directions. These beams were eventually reflected back along their original directions, combined, and made to enter an eyepiece. The apparatus was so oriented that the direction of one of the beams was parallel to the known motion

of the earth in its orbit. Light traveling along this path was expected to take a longer time than light traveling along the other path which was at right angles to the first. By turning the apparatus about a vertical axis so that the second beam was now parallel to the earth's motion, the first transverse, the role of each beam was reversed. The one formerly taking the longer time was now expected to take the shorter time and the light waves from each beam reaching the eyepiece were expected to arrive with a new phase relation. If the two beams had in the first orientation of the apparatus arrived so that the crest of a wave from one beam fell on a crest from the second beam, they might in the second position be expected to arrive so that the crests did not arrive at the same time and fall one upon another. The result would be a partial destruction of the light by interference between the two sets of waves. As the apparatus was continually rotated the interference pattern seen in the eyepiece was expected to shift with the periodic change in the relative phase of the two beams, and the changing relative time of transit along each path could be measured by watching this changing interference pattern.

When the experiment was performed, there was no noticeable shift in the interference pattern, and thus no apparent effect of the supposed motion of the earth through the ether.

The perhaps obvious explanation of the failure of this experiment as a result of the motion of ether along with the earth, an explanation that would at the same time explain the absence of friction to plane-

tary motion, failed because of additional experimental evidence, in particular that resulting from an experiment in which light was sent between two rapidly rotating discs. The ether between the discs, if there was any, had no observable effect on the light passing through it. The inference was that this ether was stationary and was not dragged around by the rotating plates.

How then was the negative result of the Michelson-Morley experiment to be understood? An attempt at an explanation was made by Fitzgerald, who asked the question: May not the motion of the apparatus result in some changes in this apparatus? May not the length in the direction of motion be shortened by an amount depending on the velocity? An affirmative reply to this question would explain the failure to measure motion relative to the ether, for then the contraction of lengths parallel to the direction of motion would counteract the longer time otherwise taken by the light in traversing the distance in this direction. The assumed contraction is known as the Fitzgerald contraction, and does not depend on the material used in the construction of the apparatus, only on the ratio of the velocity of the apparatus to the velocity of light.

A possible theoretical explanation of the Fitzgerald contraction was soon given in the electron theories of Lorentz and Larmor, resulting in the same equations proposed by Fitzgerald for making transformations between moving systems having different velocities.

If solid bodies can be considered to consist of electric charges and nothing else, which seemed probable

at the time but could not be proved, then the dimensions of a body, in particular a rigid rod, will depend on the interaction of electric and magnetic forces. These forces, having their seat in the assumed ether, were shown to depend on the state of rest or motion of the body concerned with respect to this ether. It was shown by Lorentz and Larmor that the motion of such a body through the ether would result in a contraction exactly equal to the Fitzgerald contraction. Thus was the negative result of the experiment partially explained, but for the reasons given the explanation was not entirely satisfactory.

In 1905 Einstein embarked on an entirely different method of reasoning, and took a definite step toward the eradication of the difficulty. From this year dates the theory of special or restricted relativity. It is characteristic of Einstein's genius that he was able to make such a complete break with past methods of scientific reasoning.

It will be recalled that the principle of Galilean relativity stated that the laws of physics preserved their simple form under Galilean transformations from one inertial system to another, even if the two systems were in uniform rectilinear motion with respect to each other. Implicit in this statement, as well as in all of Newton's work in mechanics, was the assumption that one system of reference existed which was absolutely at rest, and to which all inertial systems could be referred. Given sufficient knowledge of the universe, it was supposed that relative motion of the type considered, uniform motion in a straight

line, could be reduced to absolute motion, whose direction and magnitude might be exactly determined.

No one had as yet found out just how this absolute motion might be determined, or to what it could be referred. The motion of the earth can be determined with reference to the sun, but this motion is not absolute motion for the sun itself is known to move with reference to the so-called fixed stars. Moreover the stars have motions of their own, as well as the entire galaxy.

Until recently it had been supposed that the ether might provide the standard of reference, to which absolute motion and absolute position could be referred. But no one has ever been able to identify a particle of ether to serve as a standard of absolute position. The possibility of doing so depends on a knowledge of whether or not the ether is itself in motion with reference to some superior frame of reference.

The negative result of the Michelson-Morley experiment showed that it is impossible to detect motion relative to the ether. It would therefore be impossible by such an experiment to detect absolute rest with respect to the ether.

With the results of this experiment at hand scientists began to ask: Will it ever be possible to detect absolute rest, absolute position, or absolute motion? To this question Einstein gave the catagorical reply, No. And in this No is contained the special or restricted theory of relativity.

Einstein has stated the principle of restricted rela-

tivity in the form: The laws of physics are invariant with respect to transformations from one inertial system to another according to the Fitzgerald-Lorentz transformation equations.

It will be seen that this statement implies more than the earlier statement of Galilean relativity. The dimensions of the apparatus used by Michelson and Morley contracted, according to the laws of Fitzgerald and Lorentz, by an amount just sufficient to hide the motion through the ether. No contraction is considered in Galilean transformations.

The principle given by Einstein thus amounts to a statement that as an absolute frame of reference the ether does not exist, and there is nothing else to which an appeal can be made. Absolute position and motion are and will probably remain forever unknowable. The uniformity of nature in all its parts is thus laid open to question.

Thus appears the introduction into science of the idea mentioned earlier, that science must confine its speculations to observable quantities and to relations between quantities that are directly observable, and must not extend its generalizations too far into regions of space and time that are not available for observation. The idea has been extended, both in the further development of the theory of relativity and in the later forms of the quantum theory. As a corollary appears the statement that questions relating to regions too far removed to permit of direct observation are at least for the present meaningless to science. Whether such questions have meaning for

purposes of philosophical discussion is also a question that has no meaning for science.

It will become evident as our considerations proceed how science has benefited by this new outlook. By limiting itself to regions in which the scientific method appears to be successful science does not admit defeat. At present science appears to progress more rapidly under the limitation. If in the future the new method leads science into the now forbidden regions, so much the better. In the meantime science has ceased to be interested in such discussions as to the nature of reality to which it can offer nothing of value. Whether or not philosophers insist on continuing the discussion is none of its business.

The ether as an absolute frame of reference has been the first of several mechanical concepts to be abandoned. Others have also fallen, notably many of those relating to the structure of the atom. Scientific understanding no longer depends on the possibility of making a mechanical model.

Besides failing to show an observable motion with respect to the ether or to any other absolute frame of reference, the Michelson-Morley experiment showed that the velocity of light in a vacuum is constant, the same for all observers whether at rest or in motion relative to the source. This result is inherent in the restricted principle of relativity. Any change in the velocity of light is exactly counteracted by the alteration of our measuring instruments according to the equations of Fitzgerald and Lorentz.

What has happened to the conception of absolute

time? That, too, has been abolished, along with absolute position and absolute motion. Let us see how this has come about.

It might occur to us to wonder what the inhabitants, if such there be, of a world as distant as some of the stars, might be doing "now." But what do we mean by "now"? Contrary to Newtonian ideas, we no longer consider that "now" exists there as well as here unless by some experiment such simultaneity can be established. The only way to establish simultaneity is to send a signal, either a light signal or an electromagnetic wave which travels with the constant velocity of light. Accordingly we send out a signal, now. It does not reach the distant world until the moment which we have called now has passed into history. The finite velocity of light provides that the distant inhabitants shall receive our signal some time after we have sent it out.

The distant inhabitants may believe that they can allow for the time of passage of the light and thus determine when the signal was sent. But can they? If they try to do so they are brought up at once against the wall of the impossibility of determining absolute motion, for the light may have been affected in some way by the velocity of the earth in space which would by the principle of relativity be forever unknowable. Knowledge on this point obviously depends on a knowledge of the absolute velocity of the light with respect to some absolute frame of reference, which knowledge is unattainable.

The only correct conclusion is that the concept of

simultaneity at distant points must be discarded. We observe that the light which has been used for signalling leaves with the constant velocity which it is always observed to have in vacuo. The observers on the distant world measure the same constant velocity for the signal as it reaches them, irrespective of their relative velocity to the earth. But what has happened to the light in the meantime? The alteration of measuring instruments according to the laws of Lorentz or the principle of relativity will provide that all observers, here, there, or in between, will always measure the same velocity for the light signal. But as to the "real" velocity, the absolute velocity of the light in space—science declines to answer.

Time as well as position and velocity is relative, relative to a specified observer, so that clocks as well as measuring rods obey the laws of Fitzgerald and Lorentz, and the principle of special relativity. As a result the measured velocity of light appears to all observers the same, and the concept of absolute simultaneity has disappeared. Each observer uses a frame of reference, a coordinate system, and a clock or a time scale which is appropriate to his condition. Every observer carries his space- and time-scales with him, and there is no assurance that the various local spaces and times of various observers are in agreement.

In fine, physical laws are invariant under Lorentz transformations from one inertial system to another. This is the restricted principle of relativity.

The idea of local spaces and times was indeed inherent in the electron theory of Lorentz, but with the

tacit assumption that one such system containing a local space and a local time was fundamental and absolute, while all others might conceivably be referred to it. Now this solid foundation has been destroyed, and no local system can be considered any more absolute than any other. Measurements made in any or all such systems can be compared by means of the Lorentz transformations, and the laws of physics are good in any one of the systems.

Can it be said, then, that there is nothing which can be called absolute? Are we forever to be limited to the subjective views of different observers who, though their measures agree, can never find out much about ultimate reality? Fortunately the reply is in the negative. Minkowski has shown how to combine space and time into something that is absolute, the same for all observers.

A special case will serve for an illustration. In a right triangle, a two-dimensional affair, the square of the length on the hypothenuse is equal to the sum of the squares of the lengths on the other two sides. In three dimensions the square of a length can be expressed in a similar manner as the sum of three squares. Minkowski continued the argument to still another dimension, making four in all. One of these four dimensions is related to time. This four dimensional arrangement is called the four-dimensional continuum, or the space-time continuum.

It was soon found that this continuum of space and time could be built up, not only from the local space and time of one particular observer, but from those

of any or of all observers. The continuum thus appeared to be absolute, not relative as were the local spaces and times of different observers. It has consequently been called "the world." Various observers, according to their motion, will automatically divide the continuum into three dimensions of space and one corresponding to time, but they will not in general make the same divisions.

It is naturally more difficult to work with four dimensions than with three, but the theory has been aided by a four-dimensional geometry previously developed by Riemann.

Just as three coordinates specify the position of a point in three-dimensional space, four coordinates in the space-time continuum specify what is called an "event," including a particular position at a particular time. These points are separated by "intervals" whose squares are given by complicated analytical expressions which in simple cases reduce to the sum of four squared terms. Lines joining the points specifying the events for a particular body are called "world lines" or geodesics. Every point on such a line specifies both the position and the time at which the body occupied that position. The world line is in truth a history of the body, including both past and present; and the future, if determinism is to be admitted.

Not only are the lengths of scales and the readings of clocks dependent on motion. According to the restricted theory of relativity the mass of a moving body undergoes changes dependent on the velocity. The mass increases as the velocity increases, becoming

large as the velocity grows large and finally becoming infinite as the velocity approaches that of light.

The mass of a moving electric charge was known from the earlier electron theories to vary with the velocity in an understandable way. For in order to accelerate the charge it was also necessary to accelerate the field of the charge. The mass, or the ratio of the force acting on the charge to the acceleration produced, thus became larger and larger as the velocity increased. This increase in mass of moving charges was detected experimentally by Kaufmann even before the theory of relativity was announced, and has since been confirmed with even greater accuracy. Just as the Fitzgerald contraction was theoretically predicted first by the Lorentz theory for charged bodies and later by relativity for bodies charged or uncharged, so now the increase in mass with velocity originally predicted for charged bodies has been predicted by the theory of relativity for bodies of any nature whatever. This too has been confirmed by observation.

The kinetic energy of moving bodies is given by the equation of relativity in a form different from that ordinarily used for bodies of small velocity, and includes the relativity increase in mass. This equation has led to a most significant result. For when the velocity is reduced to zero an amount of energy remains, an amount equal to the so-called rest mass of the body multiplied by the square of the velocity of light: $E = mc.^2$ This amount of energy is always inherent in the mass; if the mass could be transformed into radiant energy, this is the amount of energy that

would become available. Conversely, radiant energy has mass. Consequently light has weight, and light rays can be bent in passing through gravitational fields. The remarkable uses to which the equation $E = mc^2$ has been put will appear in a future chapter when the latest discoveries in the field of atomic physics are discussed.

So much for the restricted principle of relativity. Some ten years later came Einstein's general principle of relativity. Included under the new theory are forces and accelerated motions.

The guiding principle in the general theory of relativity is called the principle of equivalence. It is often illustrated by imagining that a man, a scientific observer furnished with a complete set of physical instruments for taking various measurements, is incarcerated in a windowless box that can be placed anywhere in the universe. The observer has no means of obtaining knowledge of his surroundings except as a result of the experiments he may perform inside the box. No signal of any kind can reach him from the outside.

If the box is situated on the surface of the earth the prisoner will be able to detect the gravitational field of the earth by means of his instruments. Springs sustaining weights will be stretched, objects will fall with the acceleration of gravity, and so on.

Imagine that the box has by a superhuman power been removed to some outer region of space so that it is far removed from every massive body, and that it is accelerated in some particular direction with an

acceleration equal to that of gravity at the earth's surface. By means of his instruments the observer will make exactly the same observations that he made at the surface of the earth, and nothing will inform him that now his results denote an acceleration through space whereas formerly they denoted a field of gravitational force. Nor would he be able to differentiate between these sets of observations and those he would make if the superhuman power placed the box on the circumference of a large wheel turning at exactly the proper speed. A gyroscope might tell him of his changing direction but he could explain the action of his stretched spring or his falling bodies equally well on the assumption of a field of force or an acceleration.

The principle of equivalence sums up the observations of the man in the box. For purposes of physical measurement, the force due to centripetal acceleration or to linear acceleration through space is entirely equivalent to the force experienced in a gravitational field.

A further analogy will illustrate the use to which the principle of equivalence has been put in the development of the general principle of relativity.

Suppose that a child is rolling marbles on bumpy ground. Each marble will travel in a straight line until it reaches a hump, when it will deviate either to right or left depending on which side of the hump it has struck. To the child the behavior of the marbles is not at all remarkable, but an untrained observer, watching from an upstairs window, might conceivably

be led to wonder why the marbles were continually repelled from certain spots. He might even assume the presence of a field of repellent force acting from the spots which, if he were nearer, he would recognize as humps in the ground.

The argument is that from the viewpoint of the marbles, the hump might just as well be replaced by such a repellent field of force. The behavior of the marbles would not be altered by this substitution. The curvature of the ground which constitutes the hump can, as far as the motion of the marbles is concerned, be replaced by a field of force.

In an analogous manner the general theory of relativity explains gravitational force as the observed effect of a curvature in the space-time continuum referred to above. Space-time is curved in regions near massive bodies, and consequently the world lines or geodesics are no longer what we would call straight. A further consequence is that the time scale is altered in such regions of space. Newton's law of universal gravitation has been replaced by a complicated geometrical system, which in special cases leads to Newton's law of attraction. In other cases it leads to a law of gravitation which corresponds with experimental observations not exactly explainable on the basis of Newton's law.

Of the many experimental tests of the special theory of relativity, the Michelson-Morley experiment has already been mentioned. Other early experiments agree in failing to detect absolute motion, experiments of an electrical as well as of an optical nature. The gen-

eral theory has also been confirmed by experimental results. The motion of the perihelion of the planet Mercury, or in other words the actual rotation in space of the orbit of this planet, is in complete agreement with predictions based on relativity, including Einstein's law of gravitation based on space-time curvature, and on the variation of mass with velocity. It is not in quantitative agreement with predictions based on Newtonian mechanics.

The bending of rays of starlight by the gravitational field, so called, of the sun has become well confirmed by many observations made during total solar eclipses. The observed deviation of the light is not in agreement with predictions based on the older laws. Finally the shift in the wavelength of spectrum lines in light coming from the companion to the star Sirius, denoting a slowing down of the time scale on this immensely dense star, is in complete accord with mathematical predictions based on the general theory of relativity.

Recent developments in the theory have led to the fascinating diversion of world building, of scientific speculation concerning the nature of the universe, a subject which is as perplexing to the layman as it is exciting to the initiated. We have, for instance, the Einstein universe, the deSitter universe, the expanding universe, and the pulsating universe. Other universes are in process of manufacture.

These various attempts to understand the actual universe have quite naturally led to results which are not consistent one with another, although each has its

Plate V

Total eclipse of the sun.

credentials. For example the Einstein universe, the result of an attempt to understand and interpret the cosmic rôle played by matter, contains far too much matter if astronomical estimates are to be trusted. The Einstein universe is a static universe, having curvature in the three space dimensions and none for the fourth dimension corresponding to time. On the other hand, the universe of deSitter is an empty universe with curvature in all four dimensions. This universe is essentially nonstatic, for the introduction of matter, even in small quantities, may start an expansion.

Certain observations favor deSitter's universe. DeSitter's theory predicts, and for two separate reasons, that remote objects will show evidence of recession. In the first place the curvature of the time dimension provides a varying time scale in different parts of the universe, which would show up in spectrum observations on remote objects as a displacement of the spectrum lines toward the region of longer wavelength, the red end of the spectrum. In the second place an actual expansion is predicted which would result in the same sort of spectroscopic observation. This subject will be discussed more fully in the next chapter.

The theory of relativity has proved so useful in solving some of the age-old problems of science that theorists have tried to extend it to cover all physical science. So far it has failed in two important respects.

Relativity has not as yet succeeded in including both

gravitational and electromagnetic fields in the same theory. It would be desirable to be able to show that either might be derived as a special case of a more general entity. Einstein's recent unitary field theory has been a step in this direction, but has not as yet achieved complete success.

Neither have the laws of relativity and of the quantum theory, to which a future chapter is devoted, been brought into complete accord. It is true that the laws of relativity have been adapted into the theories of atomic structure. Sommerfeld introduced into the Bohr theory the concept of the dependence of mass with velocity and of the motion of the perihelion, or more properly in this connection, the perinucleon, of an orbital electron, thereby explaining certain observations of spectroscopy. Dirac has used relativity in deriving equations applicable to an electron under the new quantum mechanics. But so far the quantum theory and the theory of relativity stand apart, two theories which meet only at certain points. A complete theory would allow the derivation of both relativity and the quantum theory or its equivalent as special cases, and at the same time account for the existence of the electron. Then could science say, Here is a picture of the world. But the picture would probably be intelligible only to a few mathematicians.

CHAPTER V

THE EXPANDING UNIVERSE

In olden times, when astronomers considered it a necessary and legitimate part of their profession to cast the horoscopes of kings and nobles, the universe was thought to consist of the earth, sun, and moon; and five known planets: Mercury, Venus, Mars, Jupiter, and Saturn; and about four thousand stars. All of creation was supposed to be included in this catalog of celestial objects.

It is natural that astronomy should have been one of the first sciences to develop. Even the most primitive of men could not escape some realization of the mysteries of a starlit sky. The earliest records that have been preserved tell us that the universe consisted of the objects just mentioned, and that the seasons were known to depend on the motions and configurations of the sun and moon. They also tell how the sun, moon, and planets were able to influence the lives and affairs of men on earth, a theory which is still believed by many as attested by the large incomes of some present-day astrologers.

With the invention of the telescope and its use by Galileo in observing celestial objects, man's conception of the universe began to change. The earth soon yielded its position of supreme importance at the cen-

ter to the sun, which in turn was later found to be far from the center of things. The number of planets was increased with the discovery of Uranus, Neptune, and now Pluto, and many of these planets were found to have satellites. With every increase in telescopic power the number of known stars increased rapidly and the limit has by no means been reached. Star clusters and nebulae were discovered, increasing both the size and the grandeur of the universe that had once been regarded as so grand with its incomplete tally of planets and a mere four thousand stars. Improved methods of measuring stellar distances and motions led Kapteyn, Shapley, and other astronomers to differentiate between a local star cloud of which the sun is a member, and the group of star clouds which had previously been called the universe. Then came the discovery that the great spiral nebulae were in fact similar to our own universe in many ways, so that they were called "island universes." More properly the entire group of star clouds, spiral nebulae, and all, should be called "the universe" in the larger sense of the original use of the word.

Astronomically the earth is a very inferior sort of object. It circulates in space around the sun, one of a vast number of similar stars, many of which far surpass the sun itself in size and brilliancy. The earth would not be visible even from the star which of all the stars is nearest to the sun. Just as the sun is not at the center of the local star cluster, this cluster is not at the center of the great accumulation of star clouds making up our local universe. Even this may

not be supreme in a system of such universes. Future increases in telescopic power may further reduce the once impressive importance of our little earth.

A few years ago, anyone reading about the expanding universe would have known that reference was being made to the expansion in man's conception of the universe resulting from his increasing ability to study more distant celestial objects and to interpret what he saw. But when one mentions the expanding universe today one refers to quite a different thing. For although our ideas concerning the universe are still growing, the universe itself now appears to be expanding in a very real sense: the more remote spiral nebulae all seem to be receding, some with very high velocities.

As astronomical measurements go, the measurement of the velocity of an object so distant that its light takes a million years and more to reach the earth is not very difficult although, as will be seen, there is sometimes a question as to the interpretation of the result. For a knowledge of the relative velocity of the earth and a star or nebula, science is indebted to the spectroscope, the same instrument that has given so much information about the structure of the atom.

In some respects it is unfortunate that the Doppler effect, revealing a relative velocity of source and observer, is not the only possible cause of a change in the frequency of light received from a distant source. Under standard conditions an atom, let us say of hydrogen, will always emit light of the same frequency, or color, as every other atom of hydrogen. If rela-

tive velocity were the only cause of a shift in frequency of starlight, it would be a simple procedure to compare the frequency of hydrogen light produced in the laboratory with the apparent frequency of hydrogen light from a star or nebula and thus measure the relative velocity of the earth with respect to this star or nebula. But if the atom of hydrogen happens to be a part of an especially dense, heavy star the frequency of the light emitted from it will be altered. Each kind of light in the spectrum will appear redder than it should be. This red shift, predicted by Einstein's theory of relativity, might however be interpreted as representing a relative velocity of the star and the earth, unless this velocity is known. When Adams recently observed the spectrum of the smaller companion of the bright star Sirius, whose velocity with respect to the earth is known, the red shift in the spectrum of this companion star could only be interpreted as the gravitational shift predicted by relativity, which result agreed with the astronomical prediction made on quite different grounds of a great density for the smaller member of this double star.

Still another possible cause for an observed shift in the frequency of starlight toward the red end of the spectrum has been studied by deSitter. An atom emitting light of a definite frequency or series of frequencies is a sort of clock. The frequencies of emitted light thus depend on the time scale which prevails in that part of space where the atom happens to be. If the time scale should be different in remote parts of the universe, as seems possible since the advent of the

theory of relativity, according to which theory time, position, and velocity are only relative quantities, then light emitted by atoms in remote nebulae would reach us with a frequency different from that of light emitted by similar atoms in an earthly laboratory. Old light would then be redder than new light. Without additional information it would be impossible to decide whether this change of frequency was caused by a relative velocity of earth and nebula or by an altered time scale in remote regions of space.

For this reason astronomers were perplexed when recent spectroscopic observations, principally by Hubble of Mt. Wilson who together with his colleagues has led the astronomical world in measuring the tremendous distances to the spiral nebulae, began to show the red shift of the light coming from these objects. It must be remembered that this red shift is in no way similar to the reddening of the setting sun, or the presumably similar reddening of light coming from remote stars as recently reported by the astronomer Stebbins, caused by the loss of the blue part of this light by scattering along the way. In the latter case there is no shift in frequency or wavelength—the blue part of the spectrum merely weakens or disappears, leaving a greater proportion of red light than was present when the light left the sun or star. The perplexity of the astronomers increased when it was found that in general the velocity of recession of the nebulae, if indeed the observed red shift was to be interpreted as a velocity, was greater for the more distant nebulae and that every one of the spiral neb-

ulae beyond a certain distance from the earth were moving away with very high speeds, while none were approaching.

At first the very fact that the observed red shift increased at greater distances suggested that possibly this shift was evidence of a reddening of light by age in a deSitter universe, the densities of the nebulae being too small to allow an interpretation of this change in light frequency as the result of an intense gravitational field. In the meantime, however, the Belgian scientist Lemaître had found by calculation that a universe such as would obey the laws laid down by relativity would of necessity expand. It could not remain static. But the amount of the expansion was indefinite, depending on the total quantity of matter in the universe, which is not known with accuracy.

It must be remembered that we are concerned at present with an account of visits to the several frontiers of science where knowledge is accumulating daily. As the information comes in it is recorded, cataloged as well as may be, and so far as possible correlated to facts and theories that have been accepted. The unknown is an essential part of every frontier, whether geographic, scientific, or what not. Hoards of books tell what has been established and what is known. This one attempts rather to tell what is now being done.

How then are the spectrum shifts observed for the remote spiral nebulae to be interpreted? At present astronomers incline to the view that a real velocity is represented, but this leads to difficulties. While not

PLATE VI
The Andromeda nebula.

necessarily out of line with the predictions of Lemaître and others, predictions which possess very little of finality because they are based not only on an incomplete knowledge of the universe as a whole but also on theories which are continually being revised as knowledge grows, the velocities appear for other reasons to be too large.

Astronomers have learned to make very good guesses as to the age of a star. It requires little scientific learning to realize that the universe must be at least as old as an average star but this conclusion appeared at first to be forbidden if the nebulae really have the high velocities ascribed to them. If the entire spectrum shift is to be ascribed to a velocity of recession, then it is a simple task to find out how long ago all the nebulae were crowded together in the center of the universe, ready to commence their outward journeys. This time apparently has a definite relation to the age of the universe. The startling conclusion was that the universe is many times younger than the stars of which it is composed.

Various attempts are now being made to avoid this impasse. Instead of a continuously expanding universe, another theoretical possibility is a pulsating universe. Such a universe has been studied in detail by Tolman, who has recently brought forward some revolutionary theories concerning the cosmos. A universe that alternates expansion with contraction could be much older than any star, even though the present rate of expansion be as high as that observed for the spiral nebulae, millions of miles per hour. The only

question is whether the universe can be allowed to pulsate in this way. Let us see what the difficulties are.

There is a law of physics, called the second law of thermodynamics, which tells us that some processes in nature are to be allowed and some are not. Ever since the middle of the last century this law has been regarded as one of the few things in nature that could really be depended on. Next to the principle of the conservation of energy it has perhaps been more revered than any other law of nature. This law of thermodynamics demands, for example, that heat energy if left to itself will always flow from a hot body to a colder one, never in the opposite direction. The implications of the law are numerous: The shuffling of a pack of cards will never restore the cards to their original order. Repeated shuffling will only serve to mix the cards more thoroughly until such a time as the cards are arranged completely at random. Equilibrium will then have been reached and further shufflings can do no more than redistribute the cards in some new but still quite random order. In the same way a beaten egg can never be restored to its original condition by continued beating.

It will thus be seen that the second law of thermodynamics demands a one-sidedness of nature. Hot bodies will cool down and give their heat energy to cooler bodies, until all of space is at one and the same temperature. In this final equilibrium condition no work can be done, no energy can be used, and no life of any form will be possible anywhere in the universe.

This state has been referred to as the heat-death of the cosmos, and until recently has appeared to be as inexorably impending as fate.

Scientists have invented a quantity that is a measure of the approach of this heat-death, a quantity which continually increases as the heat-death draws nearer. The name of this quantity has been taken from the Greek words meaning to look or to go one way. The quantity is called entropy. The essence of the second law of thermodynamics is that it forbids a decrease in entropy, and predicts a future state of maximum entropy in which no further uses of energy in any form can be made.

It is possible to imagine a process in which the entropy does not increase but remains unchanged, although such a process has never been observed. Such a process is called a reversible process. Since no increase in entropy follows the operation of the process either forward or backward, neither direction is inevitable, and either is possible. If reversible processes were possible in the universe, the final heat-death might be avoided.

Recently two possible means of escape have presented themselves. The first results from the growing preference in scientific circles for statistical mechanics instead of thermodynamics. If thermodynamics is to be superseded by the newer statistical mechanics many things can be allowed that have been expressly forbidden before.

Imagine that a drinking glass half full of water has been left on the table and forgotten for weeks. What

will happen to the water in the glass? The water will evaporate and diffuse through the air in the room. If the second law of thermodynamics is to be obeyed a final equilibrium state will result in which all the water molecules are evenly distributed throughout the room and the glass contains no liquid. This is the final state, says thermodynamics. Not necessarily so, says statistical mechanics. Each molecule has a definite velocity which is constantly being altered by collisions with other molecules. It may happen that at some remote time in the future all the molecular velocities will by chance be directed toward the glass, so that they will recombine and leave the glass in its original condition, half filled with liquid. Naturally the chances of this thing happening are pretty slim—one can compute how long he would have to wait before he could see it happen, and this time is tremendously long. But the essential point is that the process is not completely forbidden by statistical mechanics, which makes statistical studies of the individual molecules of the group, as opposed to the predictions of thermodynamics relating to the group of molecules as a whole.

The second possible means of escape from the threatening heat-death arises from the theoretical work of Tolman and others, to which reference has already been made. It is also tied up with the question of the origin of cosmic rays, a discussion of which must be reserved for a future chapter. Tolman has studied in some detail the ways in which thermodynamics and statistical mechanics are affected by the ever growing theory of relativity, and arrives at some

startling conclusions. It appears that certain types of irreversible processes can be allowed to take place simultaneously in the cosmos without producing an inevitable final state of maximum entropy and perpetual stagnation. One of these processes is the alternate expansion and contraction of the universe. Another is the changing of matter into radiant energy and of radiant energy back into matter. None of these four processes are reversible in the ordinary thermodynamic sense.

One of the most significant fruits of Einstein's theory of relativity has been the formulation of the equation relating mass with energy. According to this equation the total amount of energy in any piece of material is equal to the mass of the object multiplied by the square of the velocity of light. It thus becomes possible, knowing the amount of energy radiated by the sun or by a star in a given time, to compute the rate at which the sun or star is losing mass. We find that the sun radiates away its mass in the form of light and heat at the rate of millions of tons every second. At first sight this radiation with loss of mass appears to be a further reason for believing in the inevitability of the final heat-death predicted by thermodynamics: The sun, as well as every star, is not only cooling down, but it is also losing mass. How can it or in fact any star ever regain such lost material?

At this point Tolman steps in to demand a postponement of doomsday for the universe, if not for our own sun and system of planets. Instead of a stagnant

universe filled with radiation and cold stars, all at the same temperature, he foresees the condensation of radiation back into matter, starting the evolutionary cycle of a nebula or a star all over again from the beginning.

The cycle of the universe, according to Tolman, is then something like the following: Radiation escapes from the stars but never entirely escapes from the universe. It is prevented from doing so by the combined gravitational forces of all the members of the cosmos. At last a time comes when this gravitational attraction on the matter and radiation present in the universe starts a contraction, and when the contraction has gone far enough radiation begins to condense back into matter, perhaps into separate atoms of various chemical elements. This condensed cosmic dust is then able to collect itself into a diffuse nebula under its own gravitational attraction. The nebula becomes more and more dense, commences to rotate, and finally breaks up into smaller nebulae and stars, which now fly away from each other. In this way the life history of the universe is repeated and the final heat-death avoided. Tolman is among the first to emphasize that such a conception is of necessity far from a complete and final picture of the workings of the cosmos, being based on incomplete theoretical knowledge and on a familiarity with but a small part of the entire universe. It does, however, agree with what is already known. It allows the measured velocities of the nebulae to be regarded as real and avoids the necessity of a universe younger than its component

parts. Finally it avoids the inevitability of the threatening heat-death of all creation.

Such a pulsating universe may be of infinite age and there is apparently no reason why it should ever end. In no way does it assist in giving an answer to the question concerning the origin of all things. It merely pushes this origin back into a time infinitely remote and begs the question of ultimate origins as all theories of cosmogony must do. It does, however, make the universe as a whole immortal, at a time when science had nearly become convinced that all things must be mortal. If it is to be accepted, which is now doubted by many of the world's leading scientists because it contradicts the revered second law of thermodynamics, its acceptance will be a further step in the march of our conceptions of the universe toward greater cosmic significance, and of the earth toward less. But what does it have to say concerning the destiny of mankind? Is mankind doomed to ultimate destruction in spite of anything that science can do?

As an abode suitable for human life the earth is most certainly doomed. The sun is cooling down and will sometime be too cool to support life on earth. But if the universe is unending there exists at least the remote hope that before the sun cools down to such an extent that the earth becomes uninhabitable a few intrepid men of science will find a way to move somewhere else where life will be possible for another span of millions of years or more. Although such a thing seems impossible today one need merely recall

the immense strides made in the sciences of transportation and communication in less than fifty years. What cannot man do in a million years if he has done so much in fifty? That other possible abodes for life now exist in the universe cannot be questioned, in view of the number and variety of the celestial bodies which surround us on every side. In an unending universe the chances are very good that there will always be some part of the cosmos which is habitable. Even now, journeys to the moon or to other members of the solar system do not appear to be as nonsensical as they did a very few years ago. Necessity is the mother of invention, more so in science than in any other field. And science has shown itself to be rather capable in the way of invention.

It is very true that in two years or five years we shall be presented with quite a different view of the universe. Perhaps our present optimism is only temporary. Perhaps all our efforts toward a better life are to be foiled in the end by a cruel and remorseless universe. But if there is in reality to be no doomsday for the universe, philosophers will finally have obtained at least one thing in nature that, while subject to the laws of change and evolution, is essentially permanent and unchanging—an unchanging order of change that has always existed and will probably continue to exist. And that is something, in such a world as ours.

Plate VII
Mars.

CHAPTER VI

THE HABITABILITY OF OTHER WORLDS

Astronomers have been able to discover many impressive facts about the stars and nebulae in remote regions of space. Yet not one of them has been able to give a categorical answer to a question first asked many years before nebulae were ever discovered, a question concerning among other celestial objects some of our nearest neighbors in the solar system.

While scientists pursue the spiral nebulae into ever increasing distances this question is always kept before them, and will continue to demand their attention until a definite reply can be given. It may well be that a solution of this problem is more desired by inhabitants of the world at large than is the case for any other problem now being studied in the realm of physical science. Many columns of newsprint invariably follow the announcement of each fragmentary piece of evidence having the slightest connection with the problem, the slightest hint of a solution. For years to come men will continue to ask the question: Is the earth the only abode of life in all the universe?

Astronomers cannot be accused of negligence for having failed to produce information so universally demanded. In reality it is easier to learn many things about an object whose distance from us is measured

in millions of light-years than it is to learn other things about a planet whose distance is measured in mere millions of miles, minute fractions of a single light-year.

What is it that prevents us from achieving success in an undertaking which at first sight appears to be so simple? What forbids our increasing the magnifying power of telescopes until the smallest detail of surface feature on a planet becomes visible? It is of course the atmosphere surrounding the earth, the very atmosphere which enables us to keep alive, disturbing the light rays by irregular refractions before the light ever reaches our telescopes. We are indeed fortunate in having a sky which is not continually filled with clouds as is that of the planet Venus. Nature has given us a tantalizing taste of truth, withholding at the same time a great body of knowledge for which we are clamoring.

Thwarted in their efforts to discover whether certain neighboring planets are inhabited, astronomers have been forced to confine themselves to an investigation of physical conditions on the surfaces of these planets, in order to decide whether such conditions would be favorable for the existence and growth of living things of the type that inhabit the earth.

For the existence of life as we know it a few conditions are absolutely necessary, while certain others are highly desirable. Modern investigators in the field of biology are using the methods of physics and chemistry, as well as methods peculiar to their own field, in attempts to learn more about the conditions

necessary for the growth of the more primitive forms of vegetable and animal life. At present one can only mention the conditions necessary for the growth of various sorts of plants and animals, some primitive, some highly developed. When future researches shall have completed the outline of the evolution of man from the lowest form of living organism, it may perhaps become possible to state the necessary and sufficient conditions for the appearance and development on a planet of human beings.

The nitrifying bacteria are among the most primitive forms of life on earth. These organisms have the remarkable ability of producing organic material on a diet, if it may so be called, of nothing but inorganic or mineral substances. Their principal occupation is the oxidizing of ammonia into nitrites with the liberation of energy, in such a way that organic carbohydrates are formed from atmospheric carbon dioxide and water.

At present no connection can be found between these bacteria, or the analogous sulphur bacteria and iron bacteria, and higher forms of living things. Such bacteria could exist, however, on a planet which initially possessed no other organic material. Given a supply of water, carbon dioxide, oxygen, and ammonia, they would in time produce quantities of carbohydrates. Sunlight is not directly required for their growth, but without light and heat from the sun, water as well as carbon dioxide on the earth would be frozen solid, and the temperature would be too low for the bacteria to do their work.

The requirements for the growth of these bacteria and the resulting formation of carbohydrates are thus a moderate temperature, water, oxygen, carbon dioxide, and ammonia. If it can ever be shown, which seems doubtful at present, that the carbohydrates formed by these organisms can of themselves or with the assistance of other bacteria at present unknown combine with various substances to form chlorophyll, the proteins, and so on, the above conditions, together with the presence of sunlight and a few common mineral elements, would be the minimum requirements for the origin and growth of higher forms of life. Of course there still remains the question of the origin of these nitrifying bacteria. There is no assurance that they will always be found on any planet where conditions happen to be suitable for their growth.

It is quite a jump from such simple forms of life to the plants and animals with which we are familiar, although the physical requirements of these latter, once they have come into existence, are in some ways similar to the requirements of the bacteria just mentioned.

Before the higher forms of plant and animal life could appear, two substances had to make their debut on earth: chlorophyll and protoplasm. Where they came from, or why they appeared on earth, nobody knows.

Chlorophyll is a highly complicated chemical substance consisting of carbon, hydrogen, oxygen, nitrogen, and magnesium. Its presence in the leaves of plants causes the absorption of energy from sunlight,

resulting in the reduction of carbon dioxide taken from the atmosphere and the formation of carbohydrates from the carbon thus made available, and water. At the same time oxygen is liberated. Plants containing chlorophyll thus share with the nitrifying bacteria the ability to produce organic substances containing carbon, hydrogen, and oxygen, using up in the process inorganic carbon dioxide and water. The plants, however, as contrasted to the bacteria obtain their energy from the sunlight directly, and have a larger output of organic material. They also transcend the bacteria in being able to manufacture more complex organic substances: chlorophyll, the proteins, and protoplasm.

A cell of protoplasm is the fundamental building stone of everything that lives. While certain organic substances such as urea have been synthesized in the chemical laboratory, protoplasm has never been synthesized in this way. Chemically it consists of water; carbohydrates, fats, and proteins; oxygen and carbon dioxide; and salts of several common metals. As far as we know today, protoplasm can only be produced by living protoplasm, that is, by the physiological action of living plants or animals consisting principally of protoplasm.

Without a substance having the properties of chlorophyll there can be no plants above the fungi and other lower forms, and any animals that might happen to exist in a world without plants would soon exhaust the world's supply of the carbohydrates and proteins necessary for their subsistence. It is most unlikely that animals would ever have developed in such a

world. In general neither plants nor animals could exist in a world which did not contain protoplasm.

Biologists have not as yet been able to tell us whether life will always arise when conditions are suitable, and astronomers are consequently unable to make this assumption. If such an assumption ever becomes justifiable; if for example it is ever found that the nitrifying bacteria can develop of themselves and appear spontaneously when conditions are suitable, or that they occur everywhere in the universe, perhaps traveling from place to place on dust particles propelled by radiation pressure from the sun or another star; and if it should ever be found that the presence of these bacteria, together with the carbohydrates produced by them, will inevitably result in the development of higher forms of life, depending only on the continued suitability of the environment for their growth; then the astronomer would have a comparatively easy task. He would be able to say that since on a given planet the conditions are favorable, life had existed there in the past or would exist there in the future. Further, if the planet's age were comparable to that of the earth, he would be able to say with certainty that this particular planet must even now be the abode of higher forms of vegetable and animal life.

A further possibility is indicated by the recent report of Lipman that living micro-organisms are to be found in meteorites. If this discovery is confirmed, astronomers will have an additional reason for believing that life will develop whenever conditions are

suitable, especially if the nitrifying bacteria are always present to pave the way for the organisms that arrive on the meteorites, organisms that require carbohydrates for their nourishment. But as stated before, such a theory is at present only a dream, a forlorn sort of hope, with only the slightest basis of scientific support.

What, then, should the astronomer look for when studying living conditions on other planets? It must be remembered that he always has in mind the sort of life with which he is familiar on earth. He will therefore try to discover whether conditions on the planet in question are such as would allow the growth of protoplasm. He can safely assume the presence of the ordinary metals or their salts or oxides on any planet that is a member of the solar system, since each one of these planets including the earth must have had a common origin in the sun itself, known from a study of the solar spectrum to contain these elements. To be habitable the planet must receive sunlight in moderate intensity and must have a moderate temperature. It must have an atmosphere containing oxygen and carbon dioxide. The atmosphere must also contain water vapor, showing the presence of water on the planet. If these conditions are satisfied the planet may possibly contain life. If on the other hand they are not satisfied, the planet can certainly not contain life as we know it. This is all that the astronomer can conclude with any degree of certainty.

Before examining in detail the astronomical evi-

dence concerning conditions on the surfaces of planets in the solar system, evidence to which additions are continually being made, it may be well to look for a moment at the instruments which are used in conjunction with telescopes in such investigations, and the procedure followed in interpreting measurements made with these instruments.

It is easy to tell whether a planet or satellite has an atmosphere. For example it is known that our satellite the moon can have at most the very slightest trace of one. When the moon passes between us and a star the light from the star is cut off suddenly and the star disappears instantly, without the fading and other effects of refraction that would be observed if the starlight passed through a lunar atmosphere before being occulted. Moreover the mass of the moon is so small and consequently the surface gravity of the moon is so low that an atmosphere, however formed originally, would soon disappear. The kinetic energy of each gas molecule would ultimately carry it beyond the reach of the moon's gravitational attraction. In a similar way it is known that the innermost planet, Mercury, has too low a mass to be able to hold an atmosphere. This is especially true because of the high temperatures which must prevail on this planet, so close to the sun. Gas molecules move even faster when the temperature is raised, and consequently escape sooner. The case is as bad for the tiny planetoids circulating between the orbits of Mars and Jupiter, bodies which are even smaller than Mercury.

If the planet in question is known to have an atmosphere then the constitution of this atmosphere, as well as the speed of rotation of the planet, can be studied by means of a spectroscope attached to an astronomical telescope. The spectrum observed is of course the solar spectrum, but altered to some extent by the passage of the light through the atmospheres of the earth and of the planet under investigation, as well as by reflection at the surface of the planet. For instance, the absorption of certain parts of the solar light by oxygen in the earth's atmosphere produces one or more dark absorption lines in the spectrum of the sun. Other absorption lines are caused by water vapor, the intensity of the absorption lines being a measure of the amount of water vapor in the atmosphere.

A difficulty presents itself in any such measurement that can only be overcome by an experimental trick. The absorption lines due to oxygen may be attributed to oxygen in the sun, in the earth's atmosphere, or finally in the atmosphere of the planet under investigation. If it is desired to separate the oxygen absorption in the earth's atmosphere from that occurring in the outer layers of the sun itself, the trick consists in observing the solar spectrum at different times of day with the sun at different altitudes in the sky. When the sun is lower its light passes through more of our atmosphere before reaching the instruments than when it is high in the sky, and the spectrum absorption lines corresponding to oxygen in the earth's atmosphere will be relatively more intense. Or the east and west limbs of the sun, one approaching and

one receding, may be observed. In this case the Doppler effect separates the lines of solar origin from the telluric lines, the latter being caused by absorption in the earth's atmosphere. From such measurements it is a simple task to correct for the atmospheric absorption, the remainder of the absorption if any being due to oxygen in the outer layers of the sun.

When studying a planet a similar trick becomes desirable. If the planet is rotating with appreciable speed, and most of the planets are, one side or limb as the astronomers say will be approaching us while the other will be receding. Consequently light from one limb will be shifted toward the blue end of the spectrum according to the Doppler effect already mentioned, while light from the opposite limb will be shifted toward the red. The Doppler shift is even more apparent when the planet is approaching the earth or receding from it with maximum velocity.

In this way the absorption lines due to the planet's atmosphere are shifted out from behind the corresponding lines caused by absorption in the earth's atmosphere. The intensity of the shifted lines can be measured and the amount of oxygen in the planet's atmosphere computed. If the rotation of the planet or the velocity of the planet with respect to the earth is too slow for the success of this procedure, spectrum photographs are taken of the planet and of the moon when at the same altitude in the sky. By comparing the two one can correct for the oxygen in the earth's atmosphere.

The method of using a thermocouple at the focus

of a telescope for determining the temperature of a star or planet has already been discussed.

As has been seen the innermost planet Mercury possesses no atmosphere. Even if it had one the planet would not be a very comfortable place. It is too near the sun. Matters are made still worse by the fact that the planet probably keeps one side turned toward the sun, just as the moon always keeps one face turned toward the earth. Gravitational attraction and tidal action prevent Mercury or the moon from ever turning the other cheek.

Of the seven principal planets in the solar system beside the earth, Venus and Mars have for a long time been regarded as the most likely abodes of life. The size of each is moderate and comparable to that of the earth, Venus being very similar to the earth in size and density, while Mars is smaller and much less dense. Both are at moderate distances from the sun. With the exception of the moon and a few of the planetoids these planets are our nearest neighbors. Moreover, both are known to have atmospheres.

No one on earth has ever seen the surface of Venus. All that can be seen when a powerful telescope is turned in her direction is a very beautiful whitish-yellow object, sometimes appearing round and sometimes crescent-shaped. For a long time it has been recognized that the whiteness of the planet together with the lack of visible surface features could mean only one thing—clouds. These clouds have naturally enough hindered us in most of our studies of the planet. In the same way they would hinder the mak-

ing of astronomical observations from the surface of the planet itself. At the same time it is true that if life does exist on Venus these obscuring clouds may play a very important rôle.

During the past few years the astronomer Ross, working at Mt. Wilson, has made photographs of the planet with violet and with red light. It is much easier for red light to penetrate atmospheric haze and light clouds than for blue or violet light. Distant mountains appear blue because we see the haze between ourselves and the mountains, whereas photographs taken with red light show little or no haze and great distinctness in the image of the mountain itself. In the same way the red light from the setting sun reaches us while the blue is lost by scattering along the way. On his red photographs of Venus, Ross could see no surface markings, while on those taken in violet light he could see certain markings and details that changed quite rapidly. Prominent among these markings were banded structures near the equator of the planet and more or less parallel to it. From these photographs Ross concluded that the surface appearing in the red photographs was the upper layer of a dense bank of clouds, lying fairly low in the atmosphere of Venus and probably containing dust particles. The violet photographs, he concluded, showed a higher atmospheric level containing striated cirrus clouds, irregularly streaked and constantly changing, such as can often be seen in the upper atmosphere of the earth. The significance of these conclusions will be discussed presently.

Various attempts have been made to determine the rotation period of Venus by an observation of the movement of surface markings. One of the earliest of such observers, Schiaparelli, concluded that the planet rotated once on its axis in one siderial year, always keeping the same face turned toward the sun. Others have come to different conclusions. Barnard, who died only a few years ago and whose astronomical work bears witness to eyesight of extraordinary keenness, reported that he could see no surface detail that was not transient and illusory. For him an estimate of the rotation period of the planet was impossible. It is perhaps more important that spectroscopic observations made at the Lowell and the Mt. Wilson observatories have failed to show a rotation period of less than about two weeks. Moreover, the planet is not flattened at the poles as is the case with the earth, the sun, and in fact all astronomical objects that rotate with any considerable speed.

On the other hand evidence exists to show that the planet does rotate with moderate speed. The striations in the high level clouds observed by Ross constitute such evidence. Measurement of the temperatures of various parts of the visible surface of the planet, corresponding to a rather high atmospheric level, made at Mt. Wilson by Pettit and Nicholson show that the dark side of the planet is at a temperature of about 20° below zero on the centigrade scale, not far below the temperature on the illuminated side. The temperature of the actual surface of the planet must of course be higher. This must mean either a

fairly rapid rotation or the existence of high winds serving to equalize the temperature, possibly both; and of course a fairly large density for the atmosphere, which was suspected from the density of the cloud formations. From a consideration of all this information Ross concludes that thirty days is a reasonable assumption for the rotation period of Venus.

More distressing is the observation of St. John and Nicholson at Mt. Wilson that neither oxygen nor water vapor are detectable in the atmosphere of Venus. The apparent absence of water vapor is perhaps not so disturbing, for at the low temperatures prevailing in the upper layers of the atmosphere where cirrus clouds exist all water is in the form of fine crystals of ice, and hence would not be detectable by spectroscopic observations. The absence of oxygen is disappointing. It has been assumed that with no oxygen on the planet there could be no vegetable life, otherwise oxygen would have been produced. Of course most of the oxygen may be at lower levels and thus beyond our reach, figuratively speaking, from the outside. There are difficulties in the measurement: the planet as seen from the earth is never far from the sun and any oxygen lines in the spectrum may be hidden by lines of terrestrial origin.

At present astronomers are searching for traces of carbon dioxide. The presence of this gas would at least be evidence, however inconclusive, for the possibility of the existence of plant life on Venus. And if plants live there it is possible that animals could

also exist. Carbon dioxide has recently been detected in the atmosphere of Venus by Dunham and Adams, but until further evidence is produced it is not possible to assume that Venus is inhabited, either by plants or animals. Just now it almost looks as if the opposite view should be held. Although temperature conditions are suitable, due principally to the shielding effect of the clouds which prevent overheating of the planet by the sun which is so much nearer to Venus than to the earth, or too rapid cooling on the dark side, the gases requisite for the existence of living things have not been detected in the planet's atmosphere.

While Venus is similar to the earth in size and density, Mars is a good deal smaller as well as less dense. The atmosphere of Mars is very clear, the rare appearance of a cloud, sometimes seen at the edge of the twilight zone, being an unusual occurrence even in photographs taken with violet light. Mars is more distant from the sun than is the earth, and rotates on its axis in a little over twenty-four hours. Because of the clarity of the Martian atmosphere certain surface features of the planet have become well known from drawings and photographs made by many observers.

The most conspicuous features of the Martian landscape are the white polar caps, appearing alternately over the north and south polar regions as the seasons progress. There are also areas of ruddy hue, as well as darker areas that change in appearance with the seasons, sometimes having a dark-greenish tinge, at

other times appearing distinctly brown. The ruddy areas have been regarded as desert regions. Seasonal changes in the darker areas have been explained in various ways. Some have thought them to be caused by drifting atmospheric haze, first obscuring and then revealing the surface features. Others have wondered if they might not be areas of salt deposits, changing their appearance according to their condition of wetness or dryness as moisture is released from the polar caps and travels over the planet. Finally, some have thought that these dark areas represent vegetation.

The dark areas appear to be traversed by streaks or lines, which have been called canals. Lowell, one of the most optimistic of the astronomers who have studied this planet, believed these lines to represent an intricate system of canals that had been designed and constructed by an intelligent race of beings for purposes of irrigation, water being pumped back and forth across the planet to supply the needs of plant and animal life. The keen-eyed Barnard, on the other hand, was never able to agree with Lowell as to the sharpness of these streaks or their inter-connecting structure. The lines appear differently to different observers, and nobody has ever claimed quite so much for them as Lowell did.

There can be no oceans or sizable lakes on Mars, but water does exist there. By a spectroscopic examination, Adams and St. John have detected in the Martian atmosphere the presence of both water vapor and oxygen, though both gases exist there in much

Plate VIII
Star clouds.

smaller quantity than in our own atmosphere. The presence of oxygen is an added reason for believing that the dark areas represent patches of vegetation, but such evidence is far from conclusive.

The temperature, this time at the actual surface of the planet, has been found to be moderate on the illuminated side but well below freezing on the dark side. The atmosphere is not sufficiently dense to prevent the escape of large amounts of heat by radiation, as is the case for Venus; and to a smaller extent for the earth, especially on cloudy nights. This rapid change in temperature, and the low temperatures at night, are not the most favorable conditions for the growth of plant life, but plants can be imagined that would be able to survive. Intelligent beings who might be present could probably learn to adapt themselves and to provide the necessary means of shelter.

Studies of Mars are continually being made, particularly at the Lowell observatory, and also at Mt. Wilson and other observatories. At present the best opinions agree that Mars does contain some sort of life, probably low forms of vegetable and just possibly animal life.

Jupiter and Saturn have never been seriously considered in any search for habitable planets. Very much more remote from the sun than either the earth or Mars, they are too cold to be of much interest to us in our quest for life outside the earth. Both have atmospheres containing clouds, but living beings would have a hard time indeed in such utter cold and darkness.

If civilization on the earth does not annihilate itself in some other way before the sun cools sufficiently to make the earth inhospitable, and if means of interplanetary travel should be developed in the millions of years before this impending calamity is due to overtake us, Venus would appear to be our first hope for refuge. Venus is at least the planet that should first be explored. Mars is always cooler than the earth, and would then be out of the question.

As to the presence of life outside the solar system, one can do little more than guess. If some other star should possess a planetary system, we could not hope to see it from the earth. The more usual form of stellar evolution appears to result in a double star system, not a planetary system. All that can be said is that in view of the multitudes of stars in the universe, of all sizes, ages, and velocities, it is reasonable to conclude that a few stars may possibly have systems of planets, some perhaps similar to the one on which we find ourselves. Again it is conceivable that on one or two of these planets conditions may be favorable for the existence of life. Whether this means the necessary appearance of life on such a planet is impossible to say. Future researches should shed some light on this question. The remote possibility of the existence on some other planet of a sort of life quite unknown on earth, perhaps consisting of some fundamental substance very unlike protoplasm, should not be forgotten. One thing is certain: In all the universe the existence of intelligent human beings must be one of the very greatest rarities of nature.

The Quest for the Ultimate

CHAPTER VII

THE HERITAGE OF MODERN PHYSICS

To a scientist of the present day the term Modern Physics is not exactly synonymous with Contemporary Physics.

There is always a tendency to refer to the most recent discoveries and theories as the New Science, relegating everything that has gone before to Classical Science. Thus whereas we used to hear of the classical physics of 1890, a scientist will now speak of the classical quantum theory of 1920, a theory which at the time was regarded as presenting the greatest imaginable contrast to the physics of 1890.

Science progresses in cycles just as definitely as does the economic life of a nation. A new experimental discovery or a new theoretical viewpoint followed through to its logical scientific conclusion will open up new fields of investigation. Soon the structure rounds itself out, and some of the older scientists begin to say that the end is at last in sight, and that practically everything is known. This body of knowledge becomes the accepted science of the day.

Modern Physics has come to be practically synonymous with Electron Physics. This state of affairs can not of course be permanent, and a century hence electron physics will take its place along with rela-

tivity as a part of what will then be called the classical physics.

In this chapter, as an introduction to a discussion of the latest discoveries, we shall examine briefly the various cycles in the development of physics. It will be convenient to consider in turn: mechanics, the kinetic theory of gases, thermodynamics, optics, electricity and magnetism, x-rays and radioactivity, and the electron. This arrangement is not strictly chronological. Indeed it would be impossible to arrange these topics in strict chronological order because many of them overlap. Newton was making important contributions to optics at the very time that his theory of universal gravitation was crowning the study of mechanics. The triumph of the wave theory of light occurred much later at the time when thermodynamics was being brought to the high point of its development, and Maxwell's great theory of electricity and magnetism was well on its way.

The study of the motion of particles and physical bodies, and of the forces causing motion or resulting therefrom, is called mechanics. If the forces are in equilibrium and cannot produce any change in the motion of a particle or a rigid body, their study is called statics, which is a branch of mechanics.

Mechanics first became an exact science as a result of the famous argument, Galileo *vs.* Aristotle.

Aristotle had already been dead for some twenty centuries when the argument took place. Perhaps if he had been living there would have been no argument. No one could call the great philosopher nar-

row minded. He was, in fact, a most versatile scientist for his time, thinking ahead of most of his contemporaries. His scientific writings may have been capable of standing the passage of twenty centuries as well or better than the writings, especially the theoretical ones, of most other scientists, ancient or modern. The difficulty arose from the reverence that was held for his writings even as late as the seventeenth century, especially by the conservative church authorities. Growth implies change, lack of change is stagnation and death. And it is of the very nature of science to grow.

When Galileo observed the equal rates of fall of the light and heavy bodies which he dropped from the leaning tower, the historic hand of authority was lifted from science and the reign of the experimental method was at hand.

The experimental facts discovered by Galileo concerning the motion of falling bodies were to be of the greatest use to Newton when he formulated the famous three laws on which his studies of mechanics were based. These laws are, to a large extent, generalizations from the earlier results of Galileo, and they could never have been written unless some such experimental work had preceded them.

Newton's laws appear in every elementary textbook on physics but for completeness they will be included here:

I. Every body continues in its state of rest or of uniform motion in a straight line unless compelled by force to change that state.

II. Change of quantity of motion (i.e., change of momentum) is proportional to force, and occurs in the direction in which the force acts.

III. Action and reaction are equal and opposite.

Simple as these laws appear, they were not to be found in the writings of Aristotle, nor could they ever have been discovered except by quantitative experiment. Together with Newton's law of universal gravitation they have been the foundation of the entire mathematical structure of mechanics. Only recently with the advent of relativity have any fundamental changes or additions become necessary.

With the laws of Newton as a foundation, immensely powerful mathematical structures have been reared by Lagrange, Hamilton, Jacobi, and others, which have made possible not only an analysis of the motion of the moon, complicated as it is by the numerous perturbing attractions of the sun and the other planets, but also the dramatic discovery of the planet Neptune from a study of the perturbations pulling Uranus from its predicted path.

Newton's work brought to a climax the first great age of physics. Whether one wishes to analyze the motion of a pushcart or to predict the existence of a new planet, his laws supply the means.

It was natural that the successes attained in the study of mechanics should suggest the application of mechanical laws to the atoms and molecules which were becoming definite concepts in chemistry and physics. Thus was born the kinetic theory. Its development together with that of its companion,

thermodynamics, culminated during the first half of the nineteenth century in what may be considered the second great age of physics.

The atom is the smallest unit into which matter can be divided by chemical means and every chemical element has its characteristic atom. It is the chemical atom and its simple combination or multiple, the molecule, that has been the subject for study of the kinetic theory, a branch of physics. In this case, as in many others, the sciences progress hand in hand. Each would be to a degree helpless without the other.

Most gases consist of molecules, the exceptions being the monatomic gases, such as the rare atmospheric gases. Argon is an example. The atoms of a monatomic gas may however be spoken of as monatomic molecules.

The kinetic theory of gases, as its name implies, is concerned with the motions of the gas molecules, and the physical consequences of these motions. It was originally worked out for gases, but has been also extended to include liquids, and in some instances solids.

To undertake a study of the motion of gas molecules without ever having seen a molecule either stationary or in motion is typical of the methods of physics. The molecules and their motions are studied by their effects. In much the same way Newton studied the apparent attraction between the earth and moon, having nothing more definite to go on than the observed central acceleration of the moon toward the earth. The gravitational forces were not directly apparent. Indeed it was difficult to imagine the agent responsible

for the transmission of such forces from one point to another in space. The forces became manifest by their effects, and were considered to be real because this assumption made plausible the results that were attributed to them.

If it be assumed that gases do in fact consist of small material particles in rapid motion the effects of the motions, if not the motions themselves, can be observed by means of the Brownian movement. For example, small smoke particles in air when viewed with strong illumination under a high-powered microscope will be seen to possess violent motions to and fro, being continually agitated but never traveling very far in any one direction. The irregular assaults of the air molecules on the particles of smoke are responsible for the observed motions of the particles, and these visible motions are very good evidence for the existence of molecular motions and hence for the physical existence of the molecules themselves. The motions can also be observed as Brown first observed them, in liquids containing finely divided particles in suspension.

As was mentioned under the discussion of relativity, and will be mentioned more definitely again below, the concept of the atom or molecule as a thing of definite size, shape, and position is not always in accord with the newest scientific theories. It is more modern to speak only of quantities that are directly observable. In this connection the directly observed quantities are gas pressure and temperature. According to modern views the excellent explanation of gas

pressure as being caused by the impacts of moving molecules does not necessarily prove the existence of the motions of the molecules, or even of the molecules themselves. In view of these considerations the Brownian movement is especially interesting. The molecule and atom, so long as they behave in the good old way (which is true until they are subjected to certain recently discovered types of experiment) are the last of the definite pictorial concepts of science inherited from an age when the universe was imagined to be a vast piece of mechanism, the results of whose operation was the world apparent to the senses. To a scientist of that age nothing was reasonable that could not be represented in mechanical terms, or in terms of easily understandable pictorial concepts. This was the age when lines of force were considered to be physical realities, and when an all-prevading medium, the ether, was regarded as necessary to explain the transmission of light and heat.

The work of Maxwell, author of the theory of electricity and magnetism which was the triumph of the third great period of physics and which predicted for the first time the existence of electromagnetic waves, gave new meaning to the kinetic theory. He it was who applied the laws of probability to molecular motions, introducing the ideas of average or mean molecular velocities, and of deviations from the mean. Without these additions it is impossible to obtain an exact correlation between molecular motions and their physical results, such as temperature.

Maxwell's additions to the kinetic theory form a

bridge not only to thermodynamics, but to the most modern theories as well. The laws of probability have played an ever increasing part in modern physics until it has become an open question whether they are not in reality the basis of some of the most important physical laws.

Thermodynamics, as its name implies, first arose as a study of heat engines, but it has since become a great deal more. The laws of thermodynamics are now invoked to explain what happens in the farthest reaches of the universe, beyond the optical reach of the most powerful telescopes.

The first law of thermodynamics is simply the law of the conservation of energy, with the important inclusion of heat as a form of energy. Heat energy is in fact kinetic energy, the energy of motion of molecules in gases and liquids, or energy of vibration of the atoms and molecules in solids. For this explanation of heat energy thermodynamics is indebted to the kinetic theory, although the first law could have been and in fact was formulated without the explicit use of the explanation.

The second law has already been briefly discussed in connection with the mention of Tolman's theory of the expanding universe. It was originally obtained from a study of the efficiency of heat engines. Its use now extends throughout the universe, which can indeed be regarded as an immense heat engine of a sort. But it is a far cry from the efficiency of a steam engine to a study of the flow of time. It now appears to some scientists that an examination of the direction of in-

creasing entropy is the most scientific method for distinguishing the future from the past, or if the words are still to be permitted, effect from cause. More will be said below on the question of causality, a question that has been raised with considerable force by the new quantum mechanics.

In the meantime the great controversy on the nature of light, whether waves or corpuscules, had been raging. Nor has it as yet been settled with complete satisfaction.

Primitive men no doubt believed in a sort of corpuscular theory of light, at least as far as they gave the matter any thought. Early scientists did in fact believe that luminous sources were the centers of origin of particles which traveled through empty space and impinged on the eye. Even Newton held to the corpuscular theory, a fact that in later years when no one doubted the truth of the unadulterated wave theory, astonished many scientists.

Newton lived at a time when ancient prejudices were being overcome by quantitative experiment, and had made some of the most important contributions to the science of his age. One wonders what he would have thought could he have heard the modern dictum that light behaves sometimes as waves and sometimes as particles. He would probably have dismissed the statement as most unscientific and based on an incomplete knowledge of nature. In Newton's day the search was for ideal laws of nature, simple and fundamental. Experiment was the necessary and proper path to true scientific knowledge, and experi-

mental knowledge was to be collected and generalized into a few fundamental laws, such as the three laws of motion. Experimental results which could not be brought into consonance with such laws were sometimes discarded. Today science has so accustomed itself to accept experimental facts at their face value that it has come to the state where it will accept experimental results that are on their face self-contradictory. If carefully performed experiments disagree and appear to show, for example, that light behaves sometimes as waves and sometimes as particles; if it seems, for the time being, that no higher law will correlate and explain the two kinds of behavior; then this is a law of nature: light behaves sometimes as waves and sometimes as particles, and there is no meaning in the question as to which light really is. Reality, as known to modern science, is the summation of dependable experimental results.

During the century following Newton's age the wave theory gained in favor, principally as the result of the work of such men as Young and Fresnel, who studied the interference and diffraction of light, effects which could easily be explained on the basis of a wave theory and which could not at the time be conceived of as verifying any sort of corpuscular theory.

The assumption of the ether, an all-pervading medium in which light waves could travel, seemed not to present insuperable difficulties, although difficulties were admitted. No doubt the successes of the wave theory in other directions blinded scientists to the inconsistency of filling all space with a solid elastic me-

dium which nevertheless had no observable effect on the orbital motion of the planets around the sun. When Maxwell presented his theory of electricity and magnetism and when the electromagnetic waves predicted were later observed experimentally by Hertz and more recently by every radio listener the ether was accepted as one of the facts of nature, not capable of comprehension even by the trained minds of scientists but necessary to explain the results of observation and useful in predicting new results.

We have already seen what the modern theories of relativity have done to the ether. The ether was the alternative to action at a distance, which was to be avoided at all costs. Science had not yet learned to beg the question, as when Einstein avoids difficulties which occur at infinity by assuming the nonexistence of infinity.

Thus the latter half of the nineteenth century was the great age of the ether, and the last great age of physics before the advent of Modern Physics, the physics of the electron, radioactivity, and the quantum theory. It is the age that has recently been honored with the title, Classical Physics. Thermodynamics with its new conception of heat as a form of energy interchangeable with mechanical and electrical energy had been developed, and the truth of the famous two laws had been established. The kinetic theory of gases had led to statistical mechanics, which allowed very improbable deviations from the conditions of equilibrium and from the inevitable increase of entropy. Newtonian mechanics, with later additions in the form

of mathematical theory, gave a powerful method of unravelling the mechanical intricacies of the solar system. The wave theory of light had been established. When the experimental results of Faraday, in the first half of the century, were developed into a complete theory by Maxwell during the latter half, it was believed that the triumph of physical science was truly at hand.

Michael Faraday, the indefatigable experimenter, was to his day what Michelson has been to a more recent one.

Faraday served his scientific apprenticeship under the great chemist Davy, but it was not long before master and student became of equal stature in the scientific world, and the master was eventually far surpassed by the student. One need only recall that much of the present electrical industry owes its existence to work performed in the laboratory by Faraday, work of a purely scientific nature, to realize the prodigious amount of research which this one man managed to accomplish in a lifetime. He is remembered especially for the discovery of the laws of electromagnetic induction, the relation between electricity and magnetic fields underlying the operation of the transformer, the induction motor, and the dynamo; the laws of electrolysis and electrochemical action in general; and researches performed with electrical discharges in vacuum tubes, as well as a magnetic effect on polarized light passing through a transparent dielectric. In order to escape the over-threatening conception of action at a distance, a conception that had

plagued Newton when pondering the theory of gravitation and that had demanded an ether in which light waves could be propagated, he invented the idea of lines of electric and magnetic force, and urged the acceptance of the idea that electrical and magnetic forces as well as electrical energy and electric charges were intimately connected with what he called the medium, which might very well be identified with the luminiferous ether.

Maxwell expressed in mathematical form Faraday's law of electromagnetic induction and took over his idea of forces and stresses in the medium. The theory was found to predict the presence of electromagnetic waves which were later detected by Hertz and called Hertzian waves. The fact that the velocity of these waves turned out to be the same as the velocity of light in vacuo and to have in common with light waves a transverse vibration so that they could be polarized led naturally to the conviction that light waves were in fact of the same nature as the Hertzian waves, but of shorter wavelength. This conviction occurred with all the more force when it was noticed that a certain ratio between electric and magnetic units occurring in the theory was equal to the velocity of the waves, and also to the velocity of light. This fact lent strength to the assumption that light waves were propagated by the alternation of electric and magnetic forces.

It is no wonder that some of the physicists who grew up in this period of the triumph of the wave theory have been extremely unwilling to give up either the pure wave theory, or the ether.

The existence of the electron was suspected as early as the period when Faraday was discovering his laws of electrolysis. In the deposition of metals or the liberation of gases from electrolytic solutions, it had been plain to Faraday that a certain definite amount of charge was associated with each ion in the solution, and that the liberation of what the chemists call a mole * required always the passage of the same amount of electrical charge through the solution. Since there are a definite and constant number of atoms in a mole, whatever the element happens to be, the idea of the fundamental unit of charge necessarily appeared. The idea was perplexing to Maxwell, but he neither incorporated it in his theory nor categorically denied the possibility of its existence.

Just before the turn of the century the electron began to appear more definitely. The discovery of radioactivity and of x-rays dates from the same period. Thus were planted the seeds of modern physics which have produced such a luxuriant growth.

It is well known how Röntgen, studying the discharge of electricity through gases in partially evacuated tubes, noticed that rays were produced in the tubes that could pass through black paper, cause objects to fluoresce, and affect photographic plates. Faraday had studied similar discharges but had not been able to attain so high a vacuum as was at Röntgen's disposal, otherwise he might have made the same observation. The belief that the rays had their origin in the fluorescing walls of the tube led Becquerel to

* A mole is an amount of a chemical substance obtained by expressing the molecular weight of the substance in grams.

Plate IX
Apparatus for producing high-speed electrons.

examine other fluorescent materials, notably a sample of ore containing pitchblende, which produced the penetrating rays even when cloudy weather had prevented the exposure to sunlight which is generally necessary to make this material fluoresce.

Thus were x-rays and radioactivity discovered. It was soon found that the x-rays were produced by the impact of negatively charged particles given off from the negative terminal of the tube, the cathode, and hence called cathode rays. Soon came the discovery of radium itself by the Curies, the analysis of the radiations from it and other similar substances into alpha, beta, and gamma-rays, and the discovery that the gamma-rays were of the same nature as x-rays.

Much of the pioneer work on the electron was done by J. J. Thomson, who was led to this field through his interest in the subject of electrical discharge in gases, whether the spectacular discharge in vacuum tubes or the slow discharge of electrified bodies exposed to the air at atmospheric pressure resulting as was soon found from the ionization of air molecules. The knowledge of x-rays greatly aided this study, for x-rays are powerful ionizing agents.

Even before Thomson had completed his studies Lorentz published a theory of electricity and magnetism based on the electron or as much of it as was understood at the time. An analysis of the electrical and magnetic effects of the motion of small charged bodies led Lorentz to some of the results of relativity, such as the apparent change in the dimensions of moving bodies as well as their increase in mass.

As has already been pointed out, these predictions

of Lorentz apply only to matter consisting entirely of charged bodies. In such a case the dimensions of the body depend on the interaction of electric and magnetic forces, which are altered by the motion. Consequently a change in dimensions and in mass is to be expected. The advantage of relativity in this respect is that, although it makes the same predictions, it makes them with complete generality for all bodies whether consisting of charges or not.

Thomson caused the cathode rays to be deflected by electric and magnetic fields, and ascertained once more that they were negatively charged particles, not radiation like x-rays. Furthermore, the deflection method enabled him to measure the ratio of charge to mass of the particles, showing that the mass of the particles was very much smaller than that of the hydrogen atom.

Thomson's method to be sure gave only the ratio of charge to mass. It was the assumption of the charge as being equal to the charge on the hydrogen atom in electrolysis that resulted in the assignment of the small mass. When Millikan used his ingenious balanced oil drop method, observing the rate of fall of a minute drop carrying an electric charge and then its rate of rise in an electric field; and when his measurements showed without ambiguity the existence of a fundamental unit of charge, the charge that had been supposed but not as yet proved with the necessary accuracy to represent the unit charge of the electron, the very unit foreshadowed in Faraday's experiments in electrolysis, the electron had come into its

own. Now that the charge was known, the mass could be computed with accuracy from the ratio of charge to mass. The electron, once a hypothetical unit of charge, had finally become a particle of known mass and charge, one of the fundamental constituents of matter.

The stage was set for great discoveries.

CHAPTER VIII

THE QUANTUM THEORY

Increasing familiarity with the electron had set the stage for great discoveries. As the curtain rises, Professor Planck is hard at work with pencil and paper, seeking the solution of a puzzle. He is trying to discover why the laws of radiation are in disagreement with the results of experiment. Before the curtain falls on the last act he will have found the solution, a solution that has since 1900 provided plots for several equally exciting dramas.

Planck was especially concerned with the laws of black-body radiation. His work has also led to a drastic revision of the laws governing radiation from vibrating electric charges.

The surface of a perfectly black body when cool absorbs all of the radiation falling upon it, while other surfaces reflect at least a part of the incident radiation. It is for this reason that a rose petal illuminated by white light appears red and a leaf green. The petal absorbs green light and reflects the red while the leaf absorbs the red part of the light, using this absorbed energy in the photosynthesis of living protoplasm, and reflects the green.

A body with a perfectly black surface reflects none of the light. All is absorbed. Consequently a candle

shining in an empty room with perfectly black walls would reveal nothing but the candle itself. Since no light comes from the walls, they would be invisible.

In the absorption of radiant energy a black body becomes heated, and if the heating continues long enough the body begins to glow. It becomes visible not by reflected light as is generally the case with visible objects such as room furnishings, but by emitted light. And just as the cool black body was the most perfect absorber, so now the heated black body is the most perfect radiator. At a given temperature it emits more radiant energy per unit of surface area than any other radiating body. It no longer appears black, but it still possesses the physical properties attributed to a black body. By way of illustration, a black design painted upon a piece of white porcelain becomes brighter than the porcelain itself when the porcelain is heated to incandescence, provided that the black paint is not destroyed by the heating.

It is characteristic of radiation from a black body that the nature of the radiation depends only on the temperature of the body, never on the kind of material in the body. At moderate temperatures the radiating body appears dull red, passing through bright red to orange, and finally brilliant white or even blue-white as the temperature is raised.

It has never been possible to find a paint that would make objects perfectly black. To a physicist a black body for laboratory use calls to mind only one thing: a *Hohlraum.*

A *Hohlraum* is a hollow space, or cavity, provided with a small opening. It does not matter what material is used to line the inner wall of the cavity, for in general it is true that light entering the small opening will be reflected, absorbed, and radiated back and forth inside the cavity so that very little of it will be able to leave by means of the window. As a consequence the cavity becomes heated. Even if the inner walls are painted a brilliant white, an observer looking in through the small window will see a background that is very black indeed.

In practice the cavity is placed inside a furnace, perhaps an electric furnace, so that it can be heated. The nature of the radiation emitted from the window is then found to be very close to that of the radiation which would be emitted from a perfectly black body. When the temperature in the enclosed space is uniform, any object enclosed in the space becomes invisible. No contrast exists between the object and its surroundings, and as far as visual observation is concerned, the object might as well be absent.

The graph representing the spectral distribution of energy in black-body radiation, whose height at any point corresponds to the relative amount of energy emitted at the corresponding part of the spectrum, is in its shape, its maximum height, and in the wavelength at which most energy is emitted, characteristic of the temperature of the radiating body. This fact has proved useful in determining the temperature of the sun, and of the other more remote stars. All that is necessary is to study the relative amounts of energy

emitted by the star at various wavelengths, assume that the star behaves like an ideal radiator, then fit the proper black-body radiation curve to the result and thereby determine the temperature.

For some time it had been believed possible to derive the radiation laws governing the emission of energy from a perfect radiator. For example, it was known that when energy is used up in the acceleration of an electric charge, of which all bodies were supposed to consist, radiant energy is emitted. For this reason an oscillating electric charge, or a charge moving in a circular orbit around an attracting center of force, would act as a radiator. With the emission of energy the oscillating charge would gradually come to rest, and the charge would gradually move inward as it lost energy by radiation, finally falling into the center. From such information it was thought possible to calculate the laws of radiation from an ideal black body. These laws, however, could not be made to agree with the facts given by experiment. Only by making certain adjustments in the theoretical curves, adjustments for which no theoretical reason could be given, could the theoretical and the experimental curve be made to agree.

Planck was endeavoring to find a theoretical reason for this divergence, or better, to work out a completely new theory that could be made to agree with experiment.

The development of Planck's radiation law is an illuminating illustration of the manner in which great scientific generalizations have sometimes arisen. His

first attempt at the development of a theory based on the laws of thermodynamics yielded little success. For this reason he turned to the newer methods of statistical mechanics, which have been described elsewhere in this book.

Planck made an assumption which he intended to use as a mathematical convenience. In the completed theory this assumption was expected to disappear. The fact that this revolutionary assumption refused to disappear in the final result led to the quantum theory of radiation in a form not suspected beforehand even by its author.

Before 1900, and even some years afterward, it was a common scientific belief that radiation processes were essentially continuous. The vibrating electric charge was assumed, or better believed, to emit radiation continuously until all the energy of the vibration had been dissipated as radiant energy. The charge had then come to rest and could radiate no more unless disturbed by some outside agent. The radiation was thought to flow outward in all directions, forming spherical waves with the source at the center of the wave system. Planck's tentative assumption denied this essential continuity of the radiation process.

It was not Planck's fault that this tentative assumption refused to disappear from the result of the theory. This very assumption has since become one of the most useful scientific generalizations.

Planck assumed that the energy emitted from a vibrating charge was emitted discontinuously and in discrete units. The size of each unit was equal to the

product of a new physical constant, called Planck's constant and denoted by the symbol h, multiplied by the frequency ν of the radiation emitted. The vibrating charge would thus emit a unit $h\nu$ of radiation, later another, and so on. In the meantime the charge would continue to vibrate without the emission of radiation and without losing any of its energy.

Although the constant h was a new physical constant, it was expressed in units already known and used in physics. It is measured in units of the quantity which physicists call action. Action is equal to energy multiplied by time. Action has played an important part in the development of the science of theoretical mechanics, being included in the famous law of least action which is one of the foundations of mechanics. Only the particular amount of the physical quantity called action included in the constant h was new. The product $h\nu$ is measured in units of energy, since ν is a number of vibrations divided by a time. Energy equals action divided by time, or in other words, $h\nu$.

Planck's original idea was to work out the laws of radiation in terms of the units $h\nu$, then by a mathematical process pass over to the limiting case in which each unit $h\nu$ becomes very small and the radiation becomes continuous. The mathematical process is called integration. But although the theory in terms of the new units of energy fitted the experimental facts exactly, the completed mathematical theory corresponding to the continuous emission of energy failed in all cases to agree with the results of experiments.

Planck concluded that there must be some reality in the assumption he had tentatively made, and published his new law of radiation.

Thus was the quantum theory of radiation born. The unit of emitted energy $h\nu$ was called a quantum of energy, and h was called a quantum of the physical quantity action. h is equal to 6.55×10^{-27} units in the c.g.s. system, or this number of units of the quantity obtained by multiplying ergs and seconds, the erg being the absolute unit of energy in this system.

From the time when Planck made this assumption up to the present the constant h has played a part of ever increasing importance in physics, until now it is regarded as one of the most fundamental of the scientific constants with which we deal.

In spite of this early entrance into theoretical physics of the quantum of action and also of the idea of the quantum of energy the concept of the light quantum, now called the photon, did not appear until later.

In 1905, the same year that he published the special theory of relativity, Einstein presented an equation which has since become historic, the equation of the photoelectric effect. Verified some years later, it still serves to explain many physical observations with the greatest accuracy.

When radiation of a sufficiently short wavelength falls upon a metal surface the metal loses negative charge. Electrons are given off from the surface. Visible light, especially light in the green or blue part of the spectrum, is effective in causing electrons to

be emitted, ultraviolet light is still more so, and x-rays will cause the emission of electrons even from gas molecules. Every metal has what is called a long-wavelength limit, above which light is no longer effective in expelling electrons.

Despite all the revolutionary implications concerning the corpuscular theory of light contained in Einstein's equation of the photoelectric effect, the equation has a very simple aspect: $E = h\nu - W$. The quantity E denotes the kinetic energy of the emitted electrons; ν is the frequency of the radiation falling on the metal surface, so that $h\nu$ is the quantum of energy characteristic of this radiation as explained above; W is the amount of work necessary to pull the electron from the surface of the metal, and is called the work-function for the particular metal and surface condition.

It soon became apparent that this equation was in a measure consonant with experimental results. It was known for example that the velocity of the emitted electrons, and hence their kinetic energy, depended not upon the intensity or brightness of the light but only on its wavelength, or color. It was known that the number of emitted electrons depended on the intensity of the incident radiation. The facts are in agreement with the equation.

It cannot be said however that the equation was immediately accepted, and for a very good reason. With the equation was offered the idea of the light quantum, or light corpuscle. This concept, implicit in the equation itself, was at the time accepted by few

if indeed by anyone but Einstein himself. Earlier corpuscular theories of light had taken such a trouncing at the hands of Huygens, Young, and Fresnel, and the wave theory of light had been so well established that there was little chance for a new corpuscular theory to receive much welcome.

As a matter of fact the photoelectric effect did demand a corpuscular theory of light. Einstein's perception of this demand led to his assumption of the existence of the light quantum.

Electrons ejected from metals by incident radiation are ejected instantly, as soon as the light is allowed to fall on the metal, and continue to be emitted as long as the light illuminates the metal surface. Their instant emission forbids the assumption that they have acquired energy from an extended portion of a wavefront by a storing process. They have not had the necessary time to store the amount of energy that they are actually observed to possess. In view of the additional fact mentioned above that the energy of emission depends on the wavelength or frequency of the light, it seemed to Einstein and later indeed to every physicist that the incident energy must reach the metallic surface in corpuscular form, the energy in each corpuscle being sufficient to eject one electron. The number of incident corpuscles increases with the intensity of the light, and so does the number of photoelectrons emitted.

Complete acceptance of the idea of the light quantum and the new corpuscular theory of light did not come for more than ten years. In the meantime Ein-

stein's equation was verified with great accuracy by Millikan, who shined light of known frequency on the cleaned surfaces of various metals in a vacuum and measured the velocity and thus the kinetic energy of the emitted electrons. The experiments also gave a measurement of *h,* which agreed well with values that had been obtained in other ways. The more recent experiments of A. H. Compton, explained below, which gained for him the Nobel prize, led to the final acceptance of the existence of the light quantum as a particle, until it has become practically impossible to find a physicist who does not agree that light travels from place to place in the form of localized condensations of energy, the light quanta or photons.

Compton was able to show, both theoretically and experimentally, that when an x-ray photon collides with an electron in a material substance, the collision can be treated very much as if the colliding bodies had been two billiard balls. The laws of conservation of energy and of momentum were as applicable in the case of the photon and the electron as in the case of the billiard balls. Moreover the loss of energy of the photon resulting from the collision made itself apparent in a change of frequency or wavelength, since the value $h\nu$ of the energy and consequently the value of the frequency ν, was different after the collision, h being constant. The predicted shift in wavelength of the scattered radiation has received voluminous and adequate quantitative confirmation from experimental measurements.

In the next chapter it will become apparent how the

well-confirmed wave theory of light has been adapted to conclude the idea of the photon, and how the newer theories have shown as well that the electron can at times exhibit the characteristics of a wave system.

While the changes in radiation theory just mentioned were taking place, equally important developments in the theory of atomic structure were occurring. It was inevitable that the new ideas of the quantum theory should be put to use in the development of the theory of atomic structure, which must be bound up with the study of spectroscopy, the analysis of light emitted by atoms.

The development of the quantum theory of atomic structure has been intimately connected with the atom model proposed by Rutherford.

At the turn of the century it was becoming clear that the constituents of atoms were in part electric charges. It was even suspected that the atom consisted of electricity and nothing else. Electrons could be knocked out of metallic atoms by incident radiation and out of air molecules by x-rays. In these processes of disruption the ejected particles were all negatively charged. It was necessary, in order to account for the neutrality of atoms in their undisturbed state to assume that in each atom there was as much positive as negative electricity, and that the positive charge always remained with the matter from which the electrons were ejected. Either this positive charge was irrevocably bound to the massive part of the atom, or it was itself the massive part.

J. J. Thomson, who has done so much work on the

conduction of electricity through gases and who was a pioneer in measuring the ratio of charge to mass of the electron, took the first step in the process later completed by Millikan of identifying the electron as the ultimate and indivisible fundamental unit of charge.

Thomson supposed that the typical atom consisted of a sphere uniformly filled with positive electricity in which smaller sized negative charges were embedded. In every atom the total positive charge was equal to the total negative charge unless by some external means, radiation or electric discharge, the atom were torn apart. In that case it would have lost some of the negative charges and the remainder of the atom would show a positive charge.

As a first attempt to understand the internal construction and working of the atom, the Thomson model was in a measure successful. By its use the photoelectric effect could be more or less quantitatively explained, as well as the production of x-rays under the impact of fast electrons upon matter. Electrons in the atom could in this way be made to oscillate about their positions of equilibrium, and in the oscillation emit waves of radiant energy. If it had been known at the time how closely the photoelectric equation of Einstein gives the relation of the frequency of the emitted x-rays to the kinetic energy of the incident electrons, it would have been apparent that Thomson's ideas needed drastic revision. As it was, the need for revision came from a quite different direction.

Rutherford and his colleagues were beginning to

realize that in the alpha-particles sent out from radioactive atoms a powerful means was available for exploring the inner structure of matter and the atom. The alpha-particle, a positively charged body having approximately the mass of an atom of helium, is discharged from a radioactive atom with considerable velocity. Such a particle can penetrate several centimeters of air at atmospheric pressure, and can pass readily through thin plates of metal. Rutherford argued, Why not send these particles through metal sheets and watch what happens to the particles?

When the experiment was tried it was found that the particles were bent from their original direction, often by such large angles that it was impossible to account for the deviation as being caused by successive small but cumulative deviations resulting from the attractions of the small negative charges in Thomson's atom. Sometimes, for example, the particles were actually thrown backwards. Rutherford concluded that the particles were deflected by a powerful center of force, and that the charge on the deflecting body was positive. Accordingly he assumed that the positive charge of the atom was highly concentrated so that it occupied a space that was small in comparison with the diameter of the atom itself, and placed this concentrated positive charge at the center of the atom.

Thus arose the modern idea of the nuclear atom. The nucleus contained positive electricity, and sometimes negative electricity as well but in such relative amounts that the net charge on the nucleus was al-

ways positive. Around the nucleus, which moreover contained nearly the entire mass of the atom, were distributed negative charges. This atom model was completely successful in explaining the large deflections of alpha-particles, as well as all the facts previously explained by Thomson's model.

The nuclear atom is still with us. Recent developments that have produced new ideas concerning the distribution of the negative charges about the nucleus, as well as the structure of the nucleus itself, have left unchanged the fundamental idea of the nuclear atom as initially proposed by Rutherford.

As might have been expected, the Rutherford atom model proved to be a substantial foundation for the development of the theory of spectra. Without it, the famous theory of Bohr could never have been formulated.

Before Rutherford and Bohr, spectroscopy was in a rather unsatisfactory condition. About all that can be said for it was that tables had been prepared of the wavelengths of light given off when substances were held in a flame or in an electric discharge. Naturally, these tabulated wavelengths were useful when compounds or mixtures were to be analyzed and when attempts were made to identify elements in the sun and the stars by means of spectral analysis of their light. But the great number of unidentifiable wavelengths in the solar spectrum was an indication of the difficulties that faced the spectroscopist of the day. Nor had any relation between spectroscopy and atomic structure been shown. Only a few series of spectrum

lines, notably the series in the hydrogen spectrum discovered by Balmer and named after him, a series in which the distribution of wavelengths showed some regularity, had been discovered.

To Bohr fell the opportunity of bringing order out of what practically amounted to chaos, chaos at least in comparison with the present completeness and usefulness of the modern theories of spectroscopy. As building stones Bohr possessed the quantum theory of Planck, the photoelectric equation and the concept of the light quantum of Einstein, and Rutherford's nuclear atom; impressive building material, suited to the construction of a powerful theory.

Bohr modified Rutherford's conception of the atom to some extent by supposing that the extranuclear electrons in the atom moved in orbits around the nucleus. These orbital electrons were assumed to constitute the source of the radiation which the atom sent out. But there was an immediate difficulty. Although electrons moving in orbits could radiate, they would according to the established views of the time lose energy to the radiation and spiral into the nucleus. Leaving aside the question of what sort of an explosion would result if this should actually happen, such an electron would move faster and faster as the size of its orbit decreased, and the frequency of the emitted radiation would become greater and greater and greater. It would thus be impossible for such an electron to emit light of a definite and constant wavelength, as observed in the spectra of all luminous gases. There was the rub.

PLATE X
A spectrum.

Bohr avoided the difficulty by sidestepping it. He assumed that since the wavelengths observed did not agree with the classical ideas of radiation from an orbital electron, there must be something wrong with these very ideas. Away with them, then! Make a new assumption that would agree with observed facts.

Bohr made the startling assumption that an electron might move in an orbit around the atomic nucleus without emitting any radiant energy. Permissible orbits were chosen by the restriction that the angular momentum of the electron be an integral multiple of h divided by 2π. Then in order to allow the emission of energy he made the added assumption that occasionally such an electron might by some unimaginable process jump to a smaller orbit with the instantaneous emission of energy. Further, in line with Einstein's equation which, it should be remembered, had not as yet been shown to apply to the facts of atomic structure, he supposed that the frequency of the radiation was determined by a very similar equation, $E_2 - E_1 = h\upsilon$, E_2 *and* E_1 being the energies of the electron in the two orbits and υ being the frequency of the radiation. This frequency was somewhere in between the actual frequencies of the electron in the two orbits. In particular, according to a principle which has been called Bohr's correspondence principle, the frequency given by the rules of Bohr is very close to that of the electron in an outer orbit, relatively distant from the nucleus yet still circulating around it, where consecutive orbits are close together.

The new theory met its first test with flying colors,

and proved able to account exactly for the Balmer series of wavelengths in the hydrogen spectrum as well as other hydrogen series and series in the helium spectrum. It enabled assignment of a spectrum series to ionized helium which had been believed to belong to the hydrogen spectrum. According to the Bohr theory the ionized helium atom, having lost one of its extranuclear electrons, resembles closely the hydrogen atom except that the nucleus is different and the electron moves in a different field of force and emits slightly different wavelengths. The new theory as well proved able to predict wavelengths that should be observed in the spectra of many elements, and lists were prepared of orbital energy values and of wavelengths to be expected in electron jumps from one orbit to another. The theory has been of the greatest utility in ascribing unidentified wavelengths observed in the spectra of stars and the sun to well known elements under conditions of temperature and pressure never to be met with on earth.

In the field of x-ray spectra the Bohr theory has also been of great service. Not only has it aided in the unravelling of observations, but it has led to the idea of atomic number, which was brought forward by Moseley on the basis of the orderly arrangement of the x-ray spectra of various elements. The atomic number of an element is equal to the net positive charge on the nucleus expressed in units equal to the charge of the electron, and determines the chemical nature of the atom concerned. It may be mentioned in passing that when the elements are arranged in the

order of increasing atomic number instead of atomic weight the periodic classification of the elements, so useful to chemists, loses all its contradictions. The idea of atomic number is in complete accord with the results of Rutherford's experiments on the scattering of alpha-particles.

Bohr's theory was extended by Sommerfeld, who included elliptical orbits in which the electron was subject to the change in mass with velocity predicted by Einstein's theory, resulting in a modification of the wavelengths in agreement with observation. The theory has also been adapted to include the spectra obtained from gas molecules, the quantum rules being applied to the rotation of the molecule as a whole as well as the vibration of its parts.

Some of the most striking results of the Bohr theory have been obtained in the field of astrophysics. Here may be mentioned the recent success of Bowen in ascribing some of the spectrum lines observed in gaseous nebulae to the common elements oxygen and nitrogen under the peculiar conditions of very low pressure and temperature which exist in these remote celestial bodies. Similarly the supposed element coronium, observed in the corona of the sun during total eclipses, has been found by Menzel and Boyce to be nothing but a well-known gas whose molecules are in a peculiar state of excitation.

CHAPTER IX

QUANTUM MECHANICS

The body of contemporary scientific truth consists of experimentally observed facts and of theories which have been built upon these observations. Both facts and theories are included in the scientific outlook of the day.

It has always been the habit of man to generalize from his observations, however inaccurate and unscientific these observations may be. To the scientist the urge is all the more powerful, partly because of his confidence in experimentally determined facts, and partly because of his experience with the methods of science. Generalizations have often been necessary in order to relate and interpret the observations, as well as to point out new lines of investigation that may prove productive. Such generalizations have come to be called laws of nature.

This tendency has often misled both layman and scientist. Concepts built upon contemporary scientific generalizations have often become so well established in the minds of men that new discoveries contradicting not the original observations but the generalizations built upon them and the resulting concepts, have often been most distressing. The concept of absolute time, destroyed by experiments leading to

and verifying the theory of relativity, is still stubbornly adhered to by many who while admitting that this concept may be of no use to science persist in retaining it in the background of "reality" of whose existence they feel sure.

To paraphrase a famous saying, theories come and theories go, but experimental facts, carefully determined, never lose their validity.

With the advent of the newest form of the quantum theory, quantum mechanics, several cherished theories and concepts have had to be abandoned. No longer can an atom be pictured as a miniature solar system. No longer can an electron or even an atom be thought of as a particle and nothing else. No longer can some of the most popular ideas of causality and determinism be maintained. No longer can one believe that with instruments of the greatest accuracy and delicacy the most minute quantities may be measured with precision.

The Bohr theory of the atom and of spectroscopy was as has been seen a physical tool of immense power, and its use has led to triumph after triumph, notwithstanding certain inherent contradictions, logical difficulties, and experimental inconsistencies which it was hoped would all be cleared up in time. No doubt the theory could have been patched up to meet the requirements of experimental spectroscopy had not the demand for a newer theoretical development come from two external sources: the impact of the ideas contained in the theory of relativity, and increasing knowledge of the wave nature of matter.

Once more history has repeated itself. A new theory has been developed which explains not only those facts explained by the last theory but new facts not previously explainable by any theory. It is the sincere hope of every physicist that the occurrence will soon be repeated, and that relativity and quantum mechanics may be incorporated in an all inclusive theory, or that another revolution in thought may lead to new ideas giving a theory from which both of the present ones may follow as logical consequences.

What was the trouble with Bohr's theory?

In the first place, no logical basis had ever been found for the validity of Bohr's assumptions. No reason has been discovered for the existence of stationary states in the Bohr atom, orbits in which an electron could revolve without radiating. Neither could it be understood why the particular orbits selected from the many classically allowed orbits should have preference, nor could the real significance of the quantum numbers determining these orbits be comprehended. These hypotheses were acceptable in so far as they led to predictions in agreement with experiment, which indeed was pretty far, but there was always present the hope that the hypotheses might receive some adequate explanation.

Nor were these logical troubles the only clouds on the horizon. As experimental technique was developed it became clear that the Bohr theory was unable to explain the structure of the helium atom, which is next in complexity to the simple hydrogen atom. Further, the numerous selection rules determining

which orbits and which transitions between orbits should be allowed had no reasonable basis. They were chosen so as to bring the theory in consonance with spectroscopic observation, and had often to be revised as new observations showed the presence of wavelengths not previously observed. Finally it was difficult to see why a beam of light should behave sometimes as a train of waves, sometimes as a stream of particles.

The time was ripe for a new theory. When it arrived, its dénouement was so sudden that many physicists still find themselves gasping for breath. And the reading public, at least that part interested in the doings of the scientists, has been well nigh asphyxiated.

The wave properties of moving electrons first showed up clearly in the experiments of Davisson and Germer in 1927, and were more of a sensation than might have been expected. The possibility had already been discussed in the literature of physics. These experiments were the first of many similar ones leading to the development of the new quantum theory and later verifying it with the greatest exactness.

How can an electron, obviously a particle, behave like a wave? This question, asked at the time of the Davisson-Germer experiment, put the emphasis in the wrong place. The electron was "obviously" a particle because all previous experiments had been explainable on the assumption that it was such, a natural assumption to make in this world so full of particles of

all sorts. Now that experiments were showing that electrons might behave like waves, it should have been just as obvious that they were waves. But then arose the question, Is the electron a wave and particle, or is it a wave or particle? In the light of recent evidence it has become clear that in the statement: The electron is a wave and/or particle, the upper half of the legal conjunction must be deleted.

Let us glance backward for a moment, back to the year 1924. The Bohr theory still reigned supreme, subject to the inconsistencies mentioned above. Relativity had reached a satisfactory stage of completion, and attempts were being made to connect the theory of relativity with the quantum theory. The emphasis on observable quantities and the necessity of disregarding nonessential concepts, insisted on by relativity, was attracting attention.

Attempts were being made to find some logical basis for the hypotheses made by Bohr. One such attempt was to lead directly to the idea of electron waves, the wave mechanics, and quantum mechanics, the modern version of the quantum theory. The attempt to explain the ability of an electron to revolve continuously in a given orbit without loss of energy has all but eliminated the very idea of electron orbits.

The argument began, as very often happens, by the consideration of an analogy.

A box full of electrons moving to and fro possesses certain properties which depend on the motions of the electrons. These properties, it was found, could be analyzed by considering that the motion of each elec-

tron was in a way comparable to the vibration of a stretched string reaching across the box. The string, which might be a violin string, vibrates in a number of ways: either as a whole, in two segments, three segments, or more, subject always to the condition that the entire length of the string should contain a whole number of vibrating segments. These vibrations correspond, in the case of the violin string, to the emission of the fundamental tone or one of the overtones.

The usefulness of the analogy can be seen more clearly when it is applied to an electron moving in an orbit about an atomic nucleus. In this case the circumference of the orbit is supposed to contain a whole number of vibrating segments, or loops, and the analogy gives some indication of the reason why the electron is able to persist in the orbit rather than spiral in to the nucleus with the emission of energy, as demanded by the older mechanical laws. This analogy is due to deBroglie, and one speaks of the deBroglie waves associated with a moving electron.

These considerations, however, hardly prepared the scientific world for the shock that followed the experimental observation of these very electron waves by Davisson and Germer a few years later.

In their experiment, which at once became classic, Davisson and Germer caused a beam of electrons to impinge upon the face of a nickel crystal and observed the directions in which electrons were scattered by the crystal. The directions in which the electrons were most strongly scattered were strikingly similar

to the directions taken by x-rays diffracted from crystals in experiments designed to measure the wavelength of the rays. If indeed the electrons had a wavelength, a fact strongly indicated by the experiment, this wavelength could be computed in exactly the same way as the wavelengths of the x-rays in diffraction experiments. The electron wavelengths came out equal to the wavelengths predicted by deBroglie. Conversely, assuming the deBroglie wavelength, the experiments led to the same atomic spacing in the crystal as had previously been determined by the use of x-rays.

The diffraction of light by a grating has long been known and used in spectroscopic wavelength measurements. The analogous diffraction of x-rays by crystals, although not known for so long, was by this time an established method of determining x-ray wavelengths, or of determining the separation and arrangement of the atoms in the crystal. What could be said now for the apparent diffraction of electrons, which had always been considered to be material particles? Was it true that a wave was associated with the moving electron, or was the electron itself nothing but a wave motion? And if the electron was a wave motion, how could it have the definite amount of charge measured by Millikan?

Such was the impasse that led to the wave mechanics of Schrödinger, and the quantum mechanics of Heisenberg, and of Born and Jordan.

Other and more able writers have attempted the

thankless and to some minds useless task of explaining the wave mechanics of Schrödinger and the later theories of quantum mechanics in non-mathematical language. Such an explanation appears at present even more difficult than non-mathematical explanation of the ideas contained in the theory of relativity, though this may cease to be true after men have thought in terms of electron waves for a decade or more.

As in the case of relativity, the inherent and irresistible logic of the newer theories demands mathematical statement. All that can be included in a non-mathematical explanation is a summary of the problem, a brief statement of the general method of attack, and last and perhaps least satisfactory, an inadequate explanation of the new concepts in terms of familiar concepts most of which have been outmoded by the new theory, concepts whose full meaning can often be given only in mathematical language.

The word theory appears so often in our discussion that a former word of warning may be repeated. A theory in the scientific sense cannot be compared to the philosophical theories of the ancients, or to the untrained imaginings of the nonscientific man. A scientific theory is a consistent system of logical, usually mathematical, reasoning based on facts that have been given by experimental observation. It is generally profitable to extend the logical arguments of such a theory beyond the region already tested experimentally. Time after time such extensions have

suggested new experiments and have occasionally indicated crucial tests of the theory which have resulted in the overthrow of the theory in its entirety.

There is a growing tendency among scientists to speak of theories rather than laws of nature. So many of the scientific generalizations that had been regarded as established have been found to be untrue or true only in certain limited regions that scientists are loath to fix to their reasonings a name so strongly suggesting permanence and absolute truth as the word law. Theory as contrasted to law is subject to development and growth and more nearly fills the scientific need. It is however permissible to speak of the laws of the relativity theory or of the quantum theory, meaning the restrictions placed on physical behavior by these theories, leaving always open the possibility that the theories may later be expanded or superseded.

The new quantum theory has grown along several distinct lines, each of which leads essentially to the same result. The wave mechanics of Schrödinger, the quantum mechanics of Heisenberg and of Born and Jordan, and later a third line of reasoning followed by Dirac are the principal developments. At present it looks as though the ideas contained in Heisenberg's theory agree more closely with reality than do those of Schrödinger. It may be noted again that these theoretical developments were well under way before the successful demonstration of the existence of electron waves by the experiment of Davisson and Germer.

Schrödinger wrote a differential equation containing something derived from the wave theory of light and something derived from the dynamical theory of moving particles, together with enough scientific intuition to unite the dissimilar concepts.

Differential equations are equations expressing relations between rates of change, and have long been used in mechanics and the wave theory. In Newtonian mechanics, for example, the differential equation expressing the acceleration of a falling body can by means of the integral calculus give the distance fallen in a specified time if the initial velocity of the falling body is known. The methods of calculus have served as powerful means for the solution of problems in dynamics and in celestial mechanics, and the differential equation is generally a step in such solutions. In a similar way the differential equations of wave theory give solutions determining the propagation of the wavefront, as well as the vibrational displacement in the wave.

Schrödinger's equation is in fact a wave equation, but the wave is not necessarily a light wave. As far as the equation goes, it can refer to a wave of almost anything; in particular, the wave associated with a moving electron. What is actually determined by the equation is the probability of the existence of the electron at a given time and place, a probability which is shown by the equation to have wave characteristics. The solution thus gives the probability that the electron will for example be at a distance from an atomic nucleus corresponding to the radius of a Bohr orbit.

The waves given by wave mechanics are thus waves of probability determining the motion of an electron. If an electron in an atomic orbit is known with certainty to be always at a definite distance from the nucleus, the equation will give for the position of the electron a thin ring spread around the orbit. On the other hand if the distance of the electron from the nucleus is not known with such extreme accuracy, the ring of so-called electron-density around the nucleus is more nebulous. Instead of a point electron moving in an orbit we now have a nebulous region in which the charge density is given by the equation of Schrödinger.

Nor is the electron forgotten by the theory if it becomes detached from the atom. An electron moving in space is regarded by the theory as a wave packet such that at any point in the packet the density of charge, corresponding to the probability of the existence of the electron at that point, is given by the wave equation.

What is meant by a wave packet?

On the older wave theory, a wave packet would be produced by the interference of two long trains of waves whose wavelength differed by some small amount. Each of the long trains might be in motion, either in the same or in opposite directions. Where the two trains were so situated that the crest of a wave of one train fell upon the crest of a wave from the other, and similarly trough on trough, the two trains of waves combined to produce a large displacement, larger than would be produced by either. At

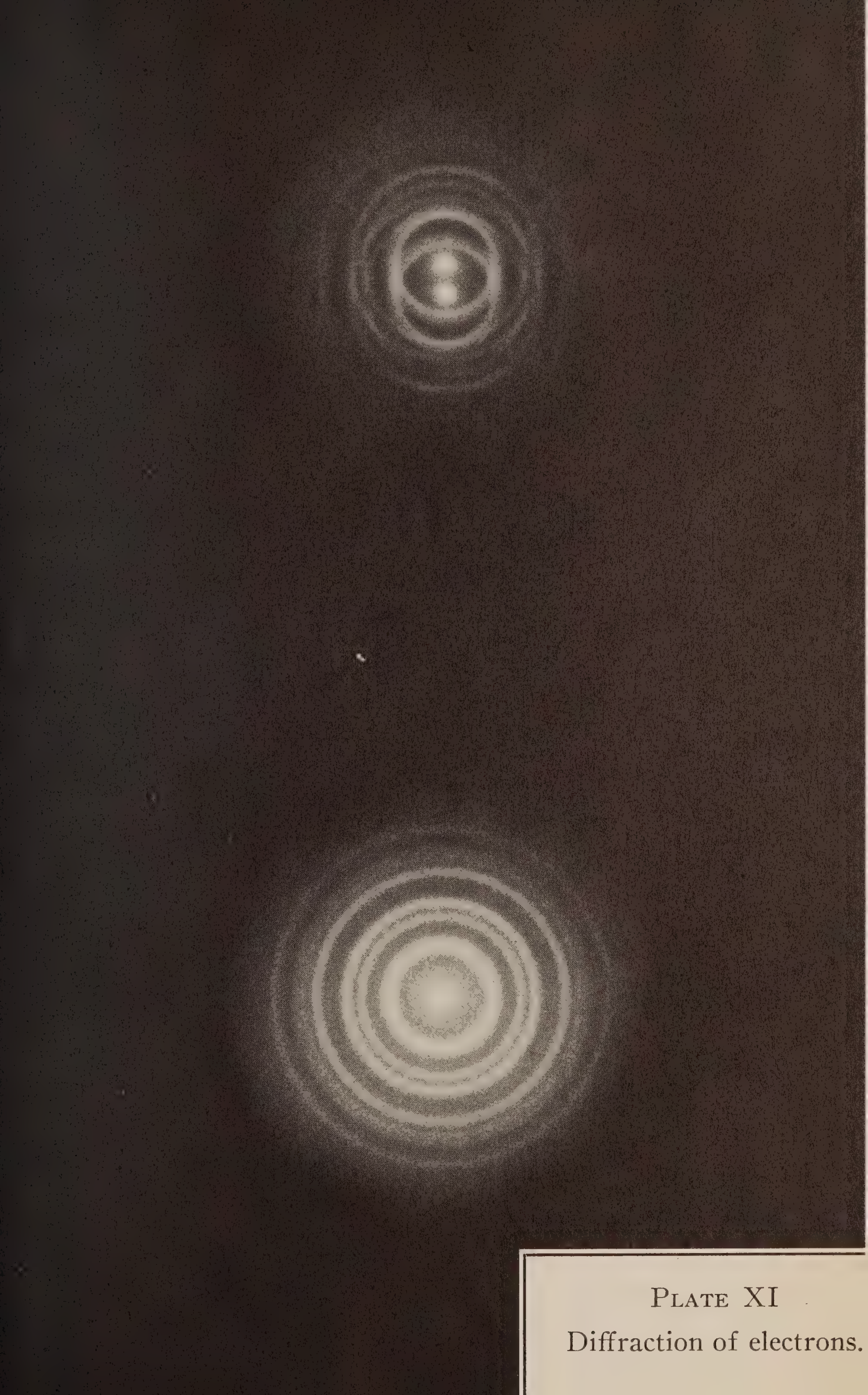


PLATE XI

Diffraction of electrons.

other places crest would fall upon trough and the two trains of waves would annul each other. Thus the interference of the two trains would result in an actual vibrational displacement only in a small part of the space covered by the trains, the region occupied by the wave packet.

The velocity of each packet, corresponding to and being equal to the velocity of the electron which according to wave mechanics is the wave packet, is the so-called group velocity of the waves, whatever happens to be the velocity of each wave train. Space is considered to be full of wave trains whose interference becomes apparent as electrons, protons, and in general, matter.

It must be emphasized that the waves do not generally exist in ordinary everyday space. They exist in what is called configuration space, the mathematical space appropriate for analytical description and used extensively in probability computations. Such a space can have any number of dimensions, depending on the complexity of the mechanical system under consideration. To form a picture of such a space is of course out of the question.

The wave mechanics of Schrödinger thus give an explanation of the observed diffraction of electrons. This diffraction has been observed not only in the case of electrons scattered from the surface of a crystal but also for electrons passing through thin metallic foils. Here again the observed diffraction effects are quite similar to the rings observed when x-rays are diffracted by crystals, and the measured wave-

length corresponding to the electron waves comes out in good agreement with the wavelength predicted for these waves.

In the meantime a new quantum theory was being worked out by Heisenberg, starting not with a combination of wave and corpuscular theory, but with assumptions of a very different sort.

It will be recalled that the quantum theory of Bohr was founded on hypotheses relating to electronic orbits in the atom. Such hypotheses appeared reasonable in view of the known constitution of the atom and by analogy with the constitution of the solar system for which the laws of mechanics were known to be valid. But no one had ever seen, nor can one ever hope to see, an electron moving in an orbit about an atomic nucleus. In view of the development of the theory of relativity, in which concepts not proving fruitful were regarded as meaningless, it began to be suspected that the concept of electronic orbits might as well be a meaningless concept. Certainly it is meaningless for experimental physics, since these orbits are not available for direct observation.

Might not the difficulty with the Bohr theory be traced to its development from hypotheses which in the above sense have no meaning? Might not a theory based only on observable quantities be found more useful and lead to deductions more in accord with experiment? It was Heisenberg who asked these questions, and it was he who replied definitely in the affirmative.

In spectroscopy the observed quantities are the wavelengths or frequencies of the light analyzed by

the spectroscope. Corresponding to these observed quantities are energy levels in the atom, quantities which are connected with the observed frequencies so closely that these too may be considered to be given by direct observation. Then, said Heisenberg, let us build a theory upon these observed quantities and on relations that may be found between them. Let us discard the conception of electronic orbits and of jumps from orbit to orbit.

Heisenberg's theory was greatly aided when Born and Jordan showed how a previously developed branch of mathematics could be used in classifying relations between the quantities considered by the theory, such as energy levels. In a similar manner the theory of relativity was aided in its development from the original ideas of Einstein by the generalized geometry of Riemann that had already been in existence for some time. The mathematical apparatus invoked by Born and Jordan was the matrix, a rectangular array of numbers in rows and columns. The observed quantities could be fitted into such an array, and the rules of mathematics relating to operation with matrices could then be applied to derive the mathematical consequences of the quantities observed.

It will be of interest to examine two particular steps in the development of Heisenberg's theory, the commutation rule and the uncertainty principle.

Since matrices have mathematical properties that are in many ways different from the properties of ordinary numbers, it should not surprise anyone to read that $pq - qp$ is not equal to zero. If the quantities p and q were ordinary algebraic quantities the

difference of pq and qp would of course vanish. Heisenberg has shown that in fact the difference of the products of p and q, and of q and p, is equal to a function involving Planck's constant. This statement is called Heisenberg's commutation rule. p represents the momentum, q represents a coordinate of position, of an electron or an electronic system. From this relation Heisenberg has been able to derive all of the results of the Bohr theory that were in agreement with experiment, as well as many new ones.

The uncertainty principle of Heisenberg has become one of the most widely invoked principles of physical science. Let us examine it.

How accurately is it possible to determine the position and velocity of an electron? As accurately as we please, said the older theory, provided we have at our disposal apparatus of the required delicacy. Not at all, says Heisenberg through the uncertainty principle. Apparatus of more than a certain delicacy will do us no good. There is a limit imposed by physical law which transcends all experimental possibilities.

To show this impossibility, Bohr has discussed the observation of an electron by means of a gamma-ray microscope. No such microscope has as yet been built, but the analysis of crystal structure by the diffraction of x-rays gives some meaning to the proposed experiment. Though not adapted to use with a microscope, short wave radiations have been used in studying the structure of matter.

The long waves of ordinary light are not suited to the observation of an electron, for the electron is so

much smaller than the length of a single light wave that the progress of the wave through space would not be much affected by the electron. Consequently it would be impossible to see the electron in such light. Even x-rays have too long a wavelength and the shorter gamma-rays are accordingly invoked.

Let us focus our gamma-ray microscope on a region traversed by moving electrons. When an electron comes into the field of view of the microscope we can determine its position and try to measure its velocity as it passes.

But one thing has been forgotten. We have been thinking too much about our part of the experiment and too little about the part to be played by the electron.

Gamma-radiation has a rather disastrous effect on electrons. One need only recall the photoelectric effect, which has been discussed in earlier pages. When the electron comes into the field of observation a gamma-ray must strike it or it cannot be seen. But when the gamma-ray meets the electron its effect on the electron proves overpowering. The electron at once forgets how it was moving and starts off with high speed, probably in some new direction, impelled by the energy absorbed from the gamma-ray.

In short, the process of observing the position of the electron with accuracy has rendered an exact measurement of the velocity impossible. The observed electron has been affected by the process of observation. Radiation of a longer wavelength would have less effect on the velocity of the electron but

would at the same time decrease the accuracy of the measurement of position.

In his famous uncertainty principle Heisenberg has summed up this unavoidable inaccuracy. The inaccuracy in the measurement of position of an electron multiplied by the simultaneous inaccuracy in the measurement of momentum is of the order of magnitude of Planck's constant. The principle has been derived in many ways and has always been in agreement with experiment, as might have been expected since its derivation sprang from experimental results.

The new theories appear to suit the results of experiment with great accuracy. And if one does not demand an actual picture of the inside of an atom, a demand which science would indeed hesitate to make, the theory gives a very satisfactory explanation of the internal workings of the atom.

The quantum numbers of the Bohr theory, determining the size and shape of electron orbits and the frequencies of emitted radiation, are given automatically rather than by the stilted and artificial selection rules of the older theory. Schrödinger's theory gives these numbers as the characteristic values found in the solution of his differential equations. The quantum numbers in Heisenberg's theory follow naturally from the matrix calculations. The quantum number of the lowest possible energy state is now seen to be ½ rather than 0 as had been suspected, clearing up difficulties in the band spectra observed from excited molecules, as well as the difficulty of accounting for the residual energy in crystalline substances at abso-

lute zero found from a study of such things as specific heats.

The diffraction of both photons and material particles, such as electrons and atoms, follow from Schrödinger's wave theory as a necessary consequence of the interaction of the waves associated with these particles. In Heisenberg's theory, the uncertainty of velocity resulting from the definite location of a moving particle, photon or electron, at a narrow slit or at the position of an atom in a crystal used to scatter the particles, serves to spread out the beam of particles and to produce the observed diffraction effects.

In the modern theories the idea of probability predominates. The solutions of Schrödinger's equations give the probability of the existence of a particle at a point, and the matrix mechanics of the theory of Heisenberg gives essentially the same result. The uncertainty principle of Heisenberg provides the indefiniteness in position and velocity of a particle which on Schrödinger's theory results from the idea of interfering wave trains.

Is it true, then, that the nineteenth century ideas of determinism and causality have disappeared?

In some ways, yes; in some ways, no. It has become impossible to predict the future position and velocity of a single particle. The process of observation, giving data that are needed for the prediction, may so alter the velocity of the particle that there is no apparent continuity in the problem. There remains, however, the possibility of making statistical predictions. No evidence exists to show that the statistical

laws of thermodynamics and of statistical mechanics are not valid as a basis of prediction of the future behavior of a physical system. In the same way the statistical laws of the new quantum mechanics may be valid for prediction when a large number of particles are present.

It has recently become fashionable in some circles to claim that the new quantum theories have at last given a scientific argument for the existence of free will and for the absence of determinism in human affairs. It is argued that thought and consequently human action, insofar as action follows thought in human problems, is the result of the interaction of electrons and atoms in the brain. If these actions are indeterminate and the future is unpredictable, it is said that free will follows as a necessary consequence.

So little is known concerning processes of thought that the argument is rather nebulous. It does appear that in physical science at least determinism is still valid in the statistical field. This fact may very well lead to the necessity of determinism in human conduct and to the denial of free will, if indeed physical science is qualified to make the denial. It may be that no physicist knows enough of the mechanics of the brain, and no psychologist enough either of the brain itself or of the workings of the elementary physical particles which constitute the brain, to be able to make a statement having much meaning. Apparently the search for a relation between science and mysticism must still, as always in the past, be left to the philosopher.

CHAPTER X

FUNDAMENTAL PARTICLES

OUR prehistoric ancestors may have differed from ourselves, but we can be fairly certain of at least one similarity. Finding a strange egg lying on the beach or a peculiar kind of nut on the ground, there can be little doubt as to what such an ancestor would do with the egg or the nut: he would open it. Later he would examine it with a view to adding variety to his food supply, but at first his motives would probably be far removed from any desire for a new thrill for his palate. Centuries later his descendants are still opening eggs, cells, and atoms, impelled by exactly the same impulse.

If the motive for the investigation has changed but little in the intervening centuries the method has changed much. The perfection of the microscope has enabled a biologist to open smaller eggs and even living cells, and to see clearly what is inside. A still greater change has come about in the field of physics. While microscopic observation is still visual observation, more powerful but still of the same type as direct observation with the unaided eye, observation of the molecule and atom cannot be carried on in any such simple way. Atoms and molecules are far too small to allow visual microscopic observation, even with the short waves of ultraviolet light. Finding themselves

unable to look directly into the molecule or the atom physicists have been forced to develop means for probing from the outside, or for blowing up the atom to see what comes out. As will presently be seen very surprising and unsuspected things do sometimes come out as the result of such explosions.

In their investigations the ancients were limited to objects of moderate size and were able to extend their familiarity with nature to the world of small objects by conjecture alone. They were no less certain that their ideas of ultimate reality were completely true than were those scientists of a very few years ago who believed that the electron and the proton were the sole and fundamental building stones for all matter. Scientists of today, with their great assortment of delicate instruments and powerful experimental methods of research are still somewhat prone to assume, as were their predecessors both ancient and modern, that the latest discovery has brought them very close to complete and final truth. That such a view is erroneous was forcibly brought to their attention by the recent discovery of what appear to be additional fundamental elements of matter, the neutron and the positive electron or positron.

It is most doubtful that any human being will ever find out all there is to know about anything. At present the largest objects with which we are acquainted, the spiral nebulae, are about as much larger than ourselves as the smallest known objects, the electrons and protons, are smaller. This fact may possibly mean that we have reached the actual limit in both

directions. But it may as well mean that human powers of observation are able to reach only so far in a study of the very great and the very small.

In this chapter we are concerned with small things, the fundamental units out of which all things are built.

For a great many years the smallest known entity was the atom, at first the surmised atom of Democritus and later the definite chemical atom of Dalton. It has been true that each new atom-concept has lasted without change for a shorter time than its immediate predecessor, principally because with each gain in knowledge the atom has become more and more specialized. For example, the atom of Democritus was so indefinite that it could hardly be supposed to have any particular properties. It was merely the final step in the process of breaking a piece of any substance into smaller and smaller pieces. It was more of a general concept than a definite atom model. Dalton's atom on the other hand was much more specific. For any particular chemical element this atom is the fundamental unit, whose relative mass is known with certainty, whose chemical affinities have also been ascertained, and whose physical properties such as size, absolute mass, etc., are known from the kinetic theory of gases.

The atomic concept of Democritus lasted for centuries and is still valid so far as it goes. The more definite atom of Dalton lasted unchanged for less than a century. While it still serves most of the chemical purposes for which it was designed it is no longer

regarded as the ultimate unit of matter. As early as the first years of the present century it had begun to lose its fundamental position. Radioactivity was showing that the atom could be broken apart, and that the parts could be separated.

The present century has given us several atom models, each more specialized than the last, each consisting of smaller and more fundamental parts than itself, and each apparently destined to last unchanged for a shorter time. The first one of importance was the atom-model of Rutherford.

Even before the discovery of radioactivity, facts pertaining to the conduction of electricity through gases had led the great physicist J. J. Thomson and others to speculate about an atom which was supposed to consist of electrical components. Radioactivity not only increased the necessity for such an atom but was soon to give concrete evidence as to its actual structure. The atom had finally ceased to be the ultimate and indivisible atom of the chemists.

Thomson's atom, consisting of negative electrons embedded in a sphere of positive electricity, explained very well the experimental facts of gaseous conduction and ionization. It could not however be reconciled with new observations on the scattering of alpha-particles from radioactive substances, scattering which often altered by large angles the paths of alpha-particles passing through metal foils. It was in an attempt to understand these large-angle deviations in the paths of scattered alpha-particles that Rutherford hit on the theory of the nuclear atom. Negative elec-

trons, known to be present in the atom, were supposed to be distributed about the nucleus in some way yet to be determined.

That the atomic nucleus itself contained electrons as well as positive charges was also known from the facts of radioactivity, though in what state was not entirely clear. Some were certainly combined with positive charges to form alpha-particles. The nucleus was supposed to contain alpha-particles, electrons, and positively charged hydrogen nuclei or protons which are far more massive than the electrons but carry the same amount of charge. The nucleus as a whole, of course, has a net positive charge.

During the years immediately following Rutherford's announcement, research in atomic physics was especially concerned with the extra-nuclear structure of the atom. This work received great impetus when only two years after the publication of Rutherford's theory Bohr presented his theory of spectroscopy and atomic structure, based on the quantum theory of Planck and Einstein and on the atomic theory of Rutherford.

To the general reader the Bohr atom is probably better known than any other. The similarity of this atom, with electrons moving in orbits about the nucleus, to the solar system seems to have taken a firm hold on the imagination of the public, which is loath to change it for the more recent atom-model given by quantum mechanics, if indeed such an indefinite thing as a set of waves of probability in many-dimensional space can be called a model. The Bohr theory has

accomplished wonders in enabling scientists to understand the intricacies of spectra, and the theory accepted at present is proving even more powerful.

Having at last obtained a theory for the extranuclear part of the atom that quite satisfactorily explains the observations of spectroscopy, physicists are more and more turning their attention to the atomic nucleus.

It is the nucleus that determines the chemical properties of an atom. In radioactive atoms the nucleus is the source of the radiations. Moreover any transmutation of elements, whether spontaneous as in the case of the radioactive elements or artificial, must involve a change in nuclear structure. Finally, most of the energy possessed by an atom resides in the nucleus.

The atomic nucleus can be studied in many ways. Very soon after the discovery of radioactivity it was found that no ordinary kind of maltreatment, whether physical or chemical, would change the radioactive properties of an atom. Neither the application of intense heat nor of extreme cold would affect radiating power. Later, when it had become known that nearly the entire mass of an atom was concentrated in a nucleus which determined the chemical properties of the atom and was the seat of the large amounts of energy that are released during radioactive disintegration processes, processes that could neither be accelerated nor retarded by any means then known to man, it was recognized that the nucleus must be a very complicated and closely bound structure, containing very large amounts of energy.

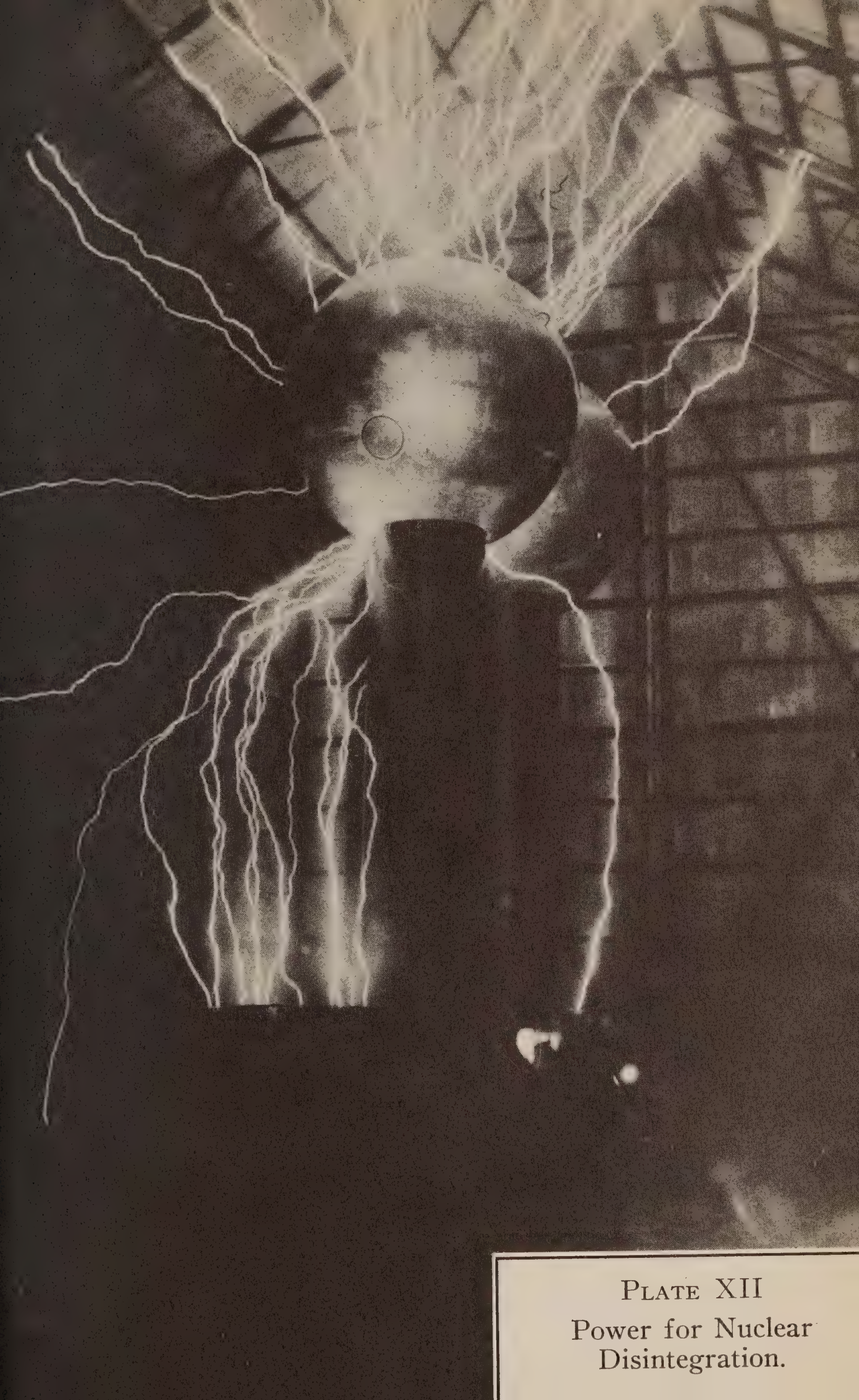


PLATE XII

Power for Nuclear Disintegration.

For several years radioactivity, which had led to its discovery, presented the most powerful means for studying the nucleus. Since alpha-particles and electrons are emitted from radioactive substances it was assumed that the nucleus contained both. The scattering of alpha-particles gave information as to the mass, size, and charge of the nucleus. The discovery by Moseley of the atomic number, relating nuclear charge to the chemical properties of an atom and clearing up difficulties in the periodic classification of the elements, helped to give the nucleus its present importance. Spectroscopy has also made its contribution to the subject.

The greatest advances in the study of the nucleus have come from transmutation or nuclear-disintegration experiments. It did not take Rutherford many years to discover that alpha-particles were able to knock protons out of nuclei, leaving a nucleus of some other chemical element having a different atomic number and atomic weight. Since then other experimenters have verified and extended the work. Although but few atoms have been transmuted in this way it is the only method that until recently has succeeded in changing one chemical element into another. The same result would of course follow if atoms were bombarded by charged atoms which had been accelerated by large electric fields, but until quite recently the electric fields obtainable have been too low, and the requisite experimental technique has not been available. Alpha-particles have been convenient because of their large energies and high velocities.

They do not require an applied electric field to set them in motion.

So far the energy obtained from such transmutation experiments had always been less than the amount of energy put in, the kinetic energy of the emergent proton being less than the kinetic energy of the incident alpha-particle. However interesting such experiments were as evidence for the actual transmutation of elements, they did not give much promise of making available the energy which is stored in such great quantities in the atom. The hope that at least a part of this energy may sometime become available has recently received an impetus from the experiments of Cockcroft and Walton, which will be described immediately. But first it is necessary to say a word about recent nuclear theories.

As was mentioned previously the nucleus has been supposed to consist of alpha-particles, protons, and electrons. It so happens however that the mass of the alpha-particle is smaller than the sum of the masses of its constituent protons and electrons as determined separately. If such were not the case the alpha-particle would probably never have been observed in experiments on radioactivity for its existence is a result of its great stability, which in turn depends on the difference in mass between the particle and its constituents. Einstein has shown that energy and mass are related according to the formula already mentioned: the total amount of energy that is contained in a given piece of material is equal to the mass of the material multiplied by the square of the velocity

of light. $E = mc^2$. Conversely, the mass of radiant energy can be calculated by the same formula. Thus the so-called "mass defect" of the alpha-particle is in reality energy of binding, and this much energy would be required to disrupt the particle.

All nuclei except the simple hydrogen nucleus have characteristic mass defects, and these figure prominently in any experiment designed to disrupt the nucleus, or to obtain atomic energy.

Let us return to the experiments of Cockcroft and Walton, performed in Rutherford's laboratory at Cambridge and since verified by several observers in different countries. Others had caused protons to be ejected from atoms under the impact of alpha-particles. Cockcroft and Walton reversed the process and caused alpha-particles to be ejected from atoms as a result of the impacts of incoming protons accelerated by electric fields of hundreds of thousands of volts. The fact that stirred the scientific world was that in a given atomic encounter the ejected alpha-particles had more energy than the incident proton. This was the first time that more energy had been obtained from such an encounter than had been put in, and newspapers printed exciting articles about the renewed hope of obtaining for practical purposes some of the energy contained in the atom. At the same time it should be remembered that very many protons must be directed at high speed toward a sample of material containing a very large number of atoms before a single encounter such as has just been described can be observed. Although in a single en-

counter the output energy is greater than the input energy, the total input energy for all the protons used is far greater than the total output energy of all the alpha-particles obtained.

The explanation came directly on the heels of the experiment. Indeed the possibility of such an effect was predicted before the experiment had been successfully concluded.

One of the elements bombarded was lithium and this will serve for an illustration. We consider a lithium nucleus containing one alpha-particle and three protons or neutrons.* Such a nucleus thus contains seven protons or neutrons, four of which are combined in the stable alpha-particle and three of which are in a sense free. It may happen that one of the incoming protons will approach this nucleus so closely that for an instant the nucleus contains a total of eight protons or neutrons. The four free protons or neutrons then proceed to combine to form another alpha-particle, and the proton is irrevocably caught. But the story is not ended. As the new alpha-particle is formed its mass decreases in the manner described above, and energy becomes available. Since the alpha-particles are so stable this energy can do but one thing: eject one or both of the alpha-particles from the nucleus with high speed. Such an occurrence is all the more probable because the new element formed, with two alpha-particles in the nucleus and nothing else, is comparatively unstable. Indeed in some of their ex-

* Since the discovery of the neutron it has been realized that the nucleus may consist partly of these new material units.

periments Cockcroft and Walton observed that two alpha-particles were ejected when a single proton hit a lithium nucleus. Lithium had been changed into helium.

More recently lithium, boron, fluorine, aluminum, and other atoms have been torn apart in a similar way with protons accelerated by lower voltages, and the investigations continue with a variety of elements. Nuclei of atoms of the newly discovered heavy hydrogen, or deuterium, have proved especially effective as bombarding agents in producing atomic disintegrations. In some cases emission of the transmutation products is delayed and the bombarded elements become artificially radioactive. One may read, for example, of radioactive table salt. Strong radioactive sources may be prepared by bombarding substances not ordinarily active, but the activity does not last very long.

Such experiments are interesting to those intent on learning more of the structure of matter, but one is forced to conclude that the day is not yet in sight when the ancient hope of rendering atomic energy available in considerable quantity may be realized.

Protons and negative electrons had previously been supposed to be the sole fundamental units of matter. But even in those days all was not well. A proton has the same quantity of charge as an electron, the former being positively charged while the latter is negatively charged. But the mass of the proton is much greater than that of the electron, being nearly equal to the mass of a hydrogen atom. It was not

easy to understand why the fundamental mass unit, the proton or hydrogen nucleus, should always have a positive charge, or why the unit of negative electricity should be associated with a particle of much smaller mass. Even now no clear answer can be given to the question, why the electron does not explode under the repulsive forces of its own charge. Other theoretical difficulties also presented themselves, notably relating to the behavior of free electrons in an atomic nucleus, those electrons which are not combined with protons to form alpha-particles.

The possibility of the existence of a neutron, or fundamental uncharged particle, had been discussed for more than a decade before such a particle appeared in an actual experiment. When at last it did appear it was entirely unexpected. In fact it was not recognized until some time after it had been observed, not only by one but by several observers.

In Germany, Bothe and Becker were engaged in experiments not unlike the disintegration experiments described above. They caused alpha-particles to bombard atoms of various elements and were interested primarily in the penetrating radiation that was produced rather than in protons that might be ejected. The radiation was detected and measured by means of the ionization produced, the same method that has for a long time been used to detect and measure gamma-radiation as well as the more penetrating cosmic-radiation. The most intense radiation was obtained by bombarding beryllium atoms with the alpha-particles. By placing absorbing screens in the proper

position any ejected protons could be absorbed and the more penetrating radiation, presumably similar to hard gamma-radiation, studied. The radiation observed had great penetrating power, being able to traverse a considerable thickness of lead.

At about the same time similar experiments were being performed in France by Irene Curie-Joliot, daughter of the illustrious Madame Curie, and her husband. An observation made by the Joliots, which they were unable to explain, was that while the intensity of the observed radiation was decreased by absorbing screens of metal it was actually increased by placing screens of such substances as paraffin in the path of the rays produced by the impact of the alpha-particles on the target.

This observation was repeated by Chadwick, again in the Cavendish laboratory of which Rutherford is the director. Clearly the increase in the ionization observed when the rays had passed through the absorbing screens was attributable to particles that had been knocked out of the absorber by the penetrating radiation. These particles could not be electrons since many more electrons would have been knocked out of metal absorbing screens, for which the effect was not observed. It was necessary to assume that protons, perhaps entire atoms, were ejected from the paraffin under the action of the penetrating rays. Such an assumption was all the more permissible since paraffin contains a large proportion of hydrogen atoms. Other materials were tried as absorbers but the greatly increased ionization was observed only when the ab-

sorber contained hydrogen, not when it contained a copious supply of electrons but no hydrogen.

At this point the impasse had been reached. If indeed the ejected particles were protons, the penetrating rays which caused their ejection could not be of the nature of gamma-rays, for the velocities and hence the kinetic energies of the protons were too great to have been obtained from such rays. Chadwick avoided the difficulty by assuming, as then seemed obvious to him and now seems obvious to many, that the penetrating rays produced by the impacts of alpha-particles on beryllium nuclei were in fact neutrons, uncharged particles of about the same mass as a proton. It was the neutrons that had caused the ejection of protons from the paraffin.

At once the great penetrating power of the neutrons was explainable. Being uncharged, they would be able to pass close to more atoms without retardation than would a charged particle, whose charge would react on the charged parts of the atoms through which it passed and retard the particle.

Although considerable doubt remains as to the real nature of the neutron, recent scattering experiments appear to show that it is in reality a new fundamental particle rather than merely an intimate combination of a proton and an electron, as was at first supposed.

Now that the secret is out, neutrons have been observed in several laboratories. They have been produced by the impact of electrically accelerated helium nuclei, or ionized helium atoms, as well as by alpha-particles, and bid fair to become one of the most

powerful means of research into the structure of the nucleus. As a source of neutrons one simply needs a mixture of beryllium and some radioactive substance emitting alpha-particles. This mixture can be contained in a glass bulb for permanence and ease of handling, since neutrons pass easily through thick glass walls. Their energy and electrical neutrality make of them ideal instruments for the disruption of atomic nuclei, and one can only guess what great advances will soon follow their discovery.

Hardly had the neutron been announced when word came of the discovery of the positive electron, a particle having the mass of the well-known negative electron but bearing a positive charge. It was first observed by Anderson, one of Millikan's associates, in a study of cosmic radiation. Word also comes from the Cavendish laboratory that Blackett has confirmed the observation under equally decisive experimental conditions.

For over twenty years scientists have possessed a convenient means for making visible the path of a rapidly moving particle, the expansion chamber developed by C. T. R. Wilson. Moisture in air, cooled by sudden expansion, condenses in droplets on ions which are formed in the gas by the passage of an alpha-particle or an electron. The tracks of the particles are thus made visible and can be photographed. If the expansion chamber is placed in a magnetic field the paths of the charged particles will be curved, the direction and amount of the curvature being a measure of the mass and charge of the moving par-

ticle. It was while observing the tracks of particles ejected from air molecules by cosmic rays that Anderson detected the positive electron, which he proposes to call the positron. Blackett's observation was of the same nature.

Physicists have thus once more been brought face to face with the problem of the ultimate and fundamental units of matter. If it is finally ascertained that these are to be three in number, namely: the negative electron, the positive electron, and the neutron, the proton being a positively charged neutron, simplicity and symmetry will have been gained and knowledge on this particular frontier pushed forward by one more stage. Theories of nuclear structure will have to be revised and scientists will continue to be challenged by the practical problems of transmutation and of atomic energy. One can feel sure that many important and exciting discoveries will result from this new stimulation to investigation in the field of atomic and nuclear physics.

CHAPTER XI

COSMIC RAYS

SPECTACULAR as were the discoveries made during 1932, the scientific world as well as that larger world that waits eagerly for each new announcement from its smaller neighbor was not spared a touch of the dramatic. For it was during the closing days of 1932 that two American physicists, each a leader of thought and possessed of strong convictions, each a Nobel Laureate, came into open disagreement on a subject of fundamental scientific importance. One maintained that the cosmic rays are streams of photons, and evidence of continuing creation; the other took the opposite view that these rays should be regarded as consisting in large part of electrons. Each produced documentary evidence in the form of experimental observations to verify his conclusions.

Several factors have contributed to the present popular interest in the cosmic, or more properly the penetrating radiation. Foremost should perhaps be placed the popular appeal inherent in the discovery of any new kind of ray. There is magic in the word. Weird stories have been woven around the villainous use of hypothetical death-rays. In the public mind the possessor of knowledge concerning any new kind of ray is often associated with the sorcerer of old, who without stirring from his tower was able to work

his will on enemies in the adjoining castle or the neighboring town. In the particular case at hand an added appeal resulted from the notion that secrets of cosmic significance were about to be revealed.

As a subject for popular discussion cosmic rays were unknown before 1926, at which time several investigators published the results of experiments that had been in progress during the years that physical research was principally concerned with the structure of the atom. Great advances had been made in the application of the physics of the atom to the physics of the stars, leading to a better understanding of stellar evolution. A broader scientific outlook was resulting from the increasing realization that certain facts relating to atomic physics could only be obtained from a spectroscopic study of stellar radiation, radiation coming from places of extreme conditions of temperature and pressure not duplicable in terrestrial laboratories.

Strangely enough, those who first observed the penetrating radiation were less anxious to study it than to eliminate its effects from their experiments. The ionization produced by this radiation discharged their electroscopes and clouded to a degree the ionization produced by radiations from the radioactive elements which were under investigation. The penetrating radiation was at first ascribed to radioactive substances in the earth or in the air, and accordingly was listed among the minor annoyances of experimental workers. As much of this radiation as could not conveniently be excluded from ionization chambers and

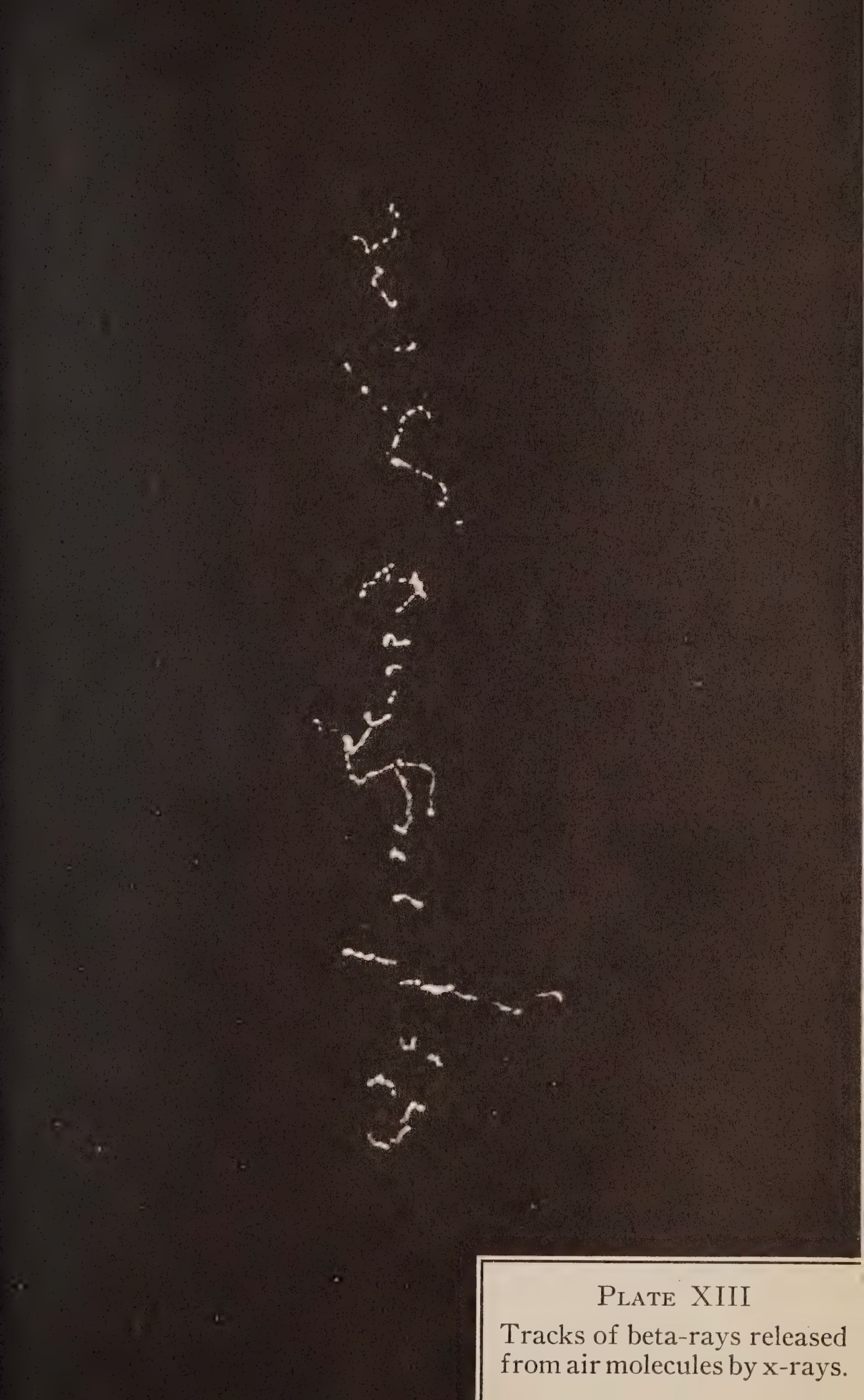


PLATE XIII

Tracks of beta-rays released from air molecules by x-rays.

electroscopes by metal shields was measured and allowed for in the experimental results. Only when it was found that this so-called residual ionization increased with altitude above the earth's surface was it realized that there might be something unusual about these penetrating rays, something worthy of more extensive examination.

Just at present the secrets of the penetrating radiation are being hotly pursued by many workers in this country as well as abroad, but for many years the only important work on the subject which was carried on in America was that of Millikan and his associates. Accordingly a brief account of this comparatively early work will not be out of place.

Shortly after it had been found that the rays in question were more intense at high altitudes Millikan undertook to measure their intensity at such great heights in the atmosphere that most of the absorbing air would lie below his instruments. Accordingly he chose balloons to carry the instruments, small balloons sent up in pairs so that the bursting of one from the decreased air pressure would still leave some support for the instruments and prevent a disastrous fall. To record the measurements a most ingenious form of apparatus was devised, small and light in weight, containing clockwork to move the photographic film on which were simultaneously recorded the rate of discharge of a sensitive electroscope and the barometric pressure indicating the altitude of the instrument. The experiment was carried out in the southwestern part of the United States and was a complete success.

As predicted, one of the balloons exploded at a height of nearly ten miles, the remaining balloon supporting the instruments as they descended slowly to earth. A complete record of the flight was registered on the photographic film, even to a record of the time of the return to earth as well as the time at which the instruments were picked up by their chance discoverer and the duration of their journey in his wagon.

An analysis of the record gave results that were in general in accord with expectations. The intensity of the rays was greatest at the highest altitude and decreased gradually as the altitude became less.

Other experiments of Millikan were performed without the use of balloons. Having sent his electroscopes to high altitudes where the radiation is strongest he naturally desired to go to the opposite extreme and find out what happened when the intensity was decreased to the vanishing point. This also presented difficulties. At sea level the radiation is so intense and so penetrating that impossibly large amounts of lead or other heavy material for purposes of shielding would be required to cut out the radiation. It was also necessary to guard against the effects of radioactive material in the earth, which is always present to a greater or lesser degree. Accordingly he chose to submerge his electroscopes in snow-fed lakes among the western mountains. The water of such lakes is known to be comparatively free from the radioactive material present in bodies of water supplied by streams, which pick up radioactive material from the adjoining land. The electroscopes, hermetically

sealed, were suspended at various depths in the lake water by means of ropes attached to a raft. After they had remained suspended at a given depth for the required length of time, a matter of hours, they were hauled up and readings were taken. In this way the absorption curve for the penetrating radiation was extended. When plotted, all the readings, including those taken at sea level, fell on a smooth curve representing the intensity of the radiation after having passed through varying amounts of absorbing material, whether air, water, or lead.

An analysis of this curve by Millikan and his associates yielded results that have become the subject of many controversies, principally scientific but often extending into the realm of theology.

Having measured the cosmic rays, the question at once arose, Whence come these rays? Millikan soon decided that they could not have their origin in the sun or the milky way, for the intensity of the radiation did not appear to depend on whether or not the sun or milky way were overhead. He concluded that the rays must come from the outer regions of space, and proceeded to analyze his curve in an attempt to discover more about the rays.

In order to understand the origin of the penetrating rays a knowledge of their wavelength, or frequency, became essential. Neither could be measured directly. Their values could only be inferred from the absorption coefficients, which were the measured quantities. The problem was complicated by the presence in the radiation of several components, each hav-

ing its own wavelength and absorption coefficient. In general, radiation of shorter wavelength or higher frequency is more penetrating than that having a longer wavelength. In order to separate the various wavelengths making up the experimental absorption curve it became necessary to use the well-known method of cut-and-try, adding together various absorption curves corresponding to assumed wavelengths in an attempt to duplicate the observed absorption curve. Accuracy was further limited by the fact that the exact numerical relation between wavelength and absorption coefficient was not known with certainty for such penetrating radiation. The relation had to be inferred from experiments performed with the much less penetrating gamma-rays and x-rays. Nevertheless Millikan obtained values of the wavelengths assumed to be present in the cosmic radiation which were in good agreement with his observations.

With the predictions made by various atomic theories in mind it thus became possible to speculate concerning the origin of cosmic radiation. Unfortunately the origin of radiation of the observed wavelengths could be ascribed to several quite different processes. One such process was the building up of heavier elements from atoms of hydrogen and helium with the release of the energy corresponding to the mass defects of the newly built atoms in the form of penetrating radiation. Millikan was inclined to favor this view. Different processes were preferred by others, notably the mutual annihilation of protons and electrons with the emission of energy. It was impos-

sible to differentiate between these theories by means of the experimental evidence then at hand. One view spoke for continuing creation, the other for original creation but present destruction.

It should be remembered that there was nothing about these early experiments to settle the question of the true nature of cosmic radiation. Since the most penetrating radiation then known to come from laboratory sources, the gamma-radiation, had been proved to consist of photons, it was only natural to assume at first that cosmic rays were of the same nature. That such assumptions are often unjustified has been shown in the case of the penetrating radiation coming from beryllium under the bombardment of alpha-particles, radiation that finally turned out to consist not of photons but of neutrons.

In the meantime a most ambitious program of cosmic-ray observation was being initiated by A. H. Compton, Nobel Laureate from Chicago. It was Compton's purpose to have simultaneous measurements of cosmic-ray intensities made at widely separated stations, both at sea level and in mountainous regions, in low and high latitudes. Although previous observers including Millikan had made measurements at different altitudes and latitudes, they had been limited in their observations to a comparatively small number of stations. By embarking on such a widely extended program, including observations at some seventy stations, Compton hoped to discover in as little time as possible whether cosmic-ray intensities did in fact depend on anything but height in the at-

mosphere. In short he desired a decisive answer to a question that had been raised as to a possible effect of the earth's magnetic field on observed cosmic-ray intensities.

The question of the variation of observed intensity with latitude is intimately connected with the question of the nature of cosmic radiation. From its penetrating power alone it might consist of photons, as is the case with light and x-rays. Or it might consist of electrons, protons, neutrons, or even atoms. It is only necessary that such particles have sufficiently enormous kinetic energies in order to have the great penetrating power observed. A variation with latitude would show that at least some of the particles in a beam of cosmic rays were charged, since the beam would then be concentrated about the magnetic poles by the earth's field. At this stage the question was of the observed penetrating power and possible latitude effects. It is clear that an experimental solution of this question must precede the solution of the related theoretical one of the nature and origin of the rays. In the absence of further information it was possible to assume the availability of almost any large amount of energy for the production of the rays, so meager is our information about the physical conditions of material in outer space.

One of the first fruits of Compton's world-wide cosmic-ray survey was a proof that the radiation was less intense near the earth's magnetic equator than in regions of moderate or high latitude, north or south. Observations previously made by Clay con-

firmed this view. It thus became evident that some at least of the observed radiation consisted of charged particles, but whether these particles were the original cosmic rays or merely so-called secondary rays produced by the impact of the primary or original rays on molecules of air at the top of the atmosphere, or on some other material, could not at the time be decided.

Some of the observers assisting in the survey took their instruments to high altitudes on snow-covered peaks. Two such observers met tragic death. In the meantime Piccard had made his famous balloon flights to an altitude of ten miles, measuring cosmic-ray intensities at various altitudes, while Regener had sent balloons with recording instruments to twice this height. Experimental facts were accumulating, soon to be used as fuel to feed the burning controversy: Does cosmic radiation consist principally of photons, or of electrons? Until this controversy can be settled with certainty theories of cosmogony, as well as theories concerning the origin of the entire material universe, are being forced to mark time and await development.

Thus it came about that Millikan and Compton, America's chief protagonists of cosmic-ray investigation, found themselves in disagreement as to the nature of cosmic rays. The clash was caused primarily by a difference in experimental results, but soon extended into the more elusive realms of interpretation.

Although Millikan's measurements had not shown any latitude effects he had, for reasons that will pres-

ently appear, predicted such an effect for measurements made at high altitudes. In the meantime Compton's observers were discovering that the radiation was in fact less intense near the equator than in northern and southern regions. It thus became apparent that at least a part of the penetrating radiation consisted of charged particles, though it was still thought possible to account for their existence by assuming that such charged particles had been knocked out of air molecules by incident photons. It very soon appeared that this view was erroneous. On the other hand the photons assumed by Millikan might conceivably be regarded as having been produced in the upper atmosphere by the action of swift electrons on molecules. Whether the original rays contained photons or electrons, the radiation reaching the earth at sea level might at the time be assumed to consist of either or both. For this reason the argument centered itself more and more on observations made at high altitudes.

Let us first follow Millikan, assume that the original cosmic-ray particles are photons similar to gamma-ray photons but more penetrating and of shorter wavelength, and see what would be observed.

For the origin of such photons one would naturally look first to the stars then to the diffuse nebulae. Nowhere else in space does sufficient energy exist in a form capable of producing such penetrating radiation. That the radiation could not come from the surface of the sun had already been established. This fact however did not preclude the possibility that other stars might be sources of such radiation, the sun being quite small and feeble in comparison with multitudes

of known stars. If produced in the center of a star, penetrating radiation would of course be entirely absorbed on the way out and could never reach us. Whether such is the case can only be inferred from theoretical deductions. It may be remarked in passing that this very process has been thought to furnish a portion of the energy radiated from the stars, as well as the sun, in the form of light and heat.

It is possible for penetrating radiation to be formed at the surface of a great star, in a process connected with the growth of what would in the case of the sun be called sunspots. In this case the radiation would probably consist principally of electrons. But assuming that high-energy photons might be produced near the surface of a star, possibly by the action of high-energy electrons, these photons would immediately eject electrons from the outer material of the star, some of which would reach the earth along with the photons. Millikan points out that even if cosmic-ray photons are formed in diffuse nebulae there is still enough material present in the nebulae and in the intervening space from which high speed electrons can be ejected, and as before the radiation reaching the earth would include some of these electrons. The observable effects of these accompanying electrons would of course depend on their kinetic energies. If this energy were rather small the electrons would all be absorbed in the upper atmosphere, in which case one would have to send balloons to very high altitudes in order to determine whether more electrons were reaching the polar regions than the equatorial regions. If on the other hand the velocities of the accompany-

ing electrons were very high, latitude effects should be observable at sea level. For such reasons Millikan predicted a latitude effect for ionization observed in the upper regions of the atmosphere, having found none at sea level. It may be noted that in order to be able to penetrate the earth's atmosphere and be observed at sea level an incoming electron would require an energy corresponding to billions of volts.

The assumption that the primary beam of cosmic rays incident on the outer atmosphere of the earth consists entirely of photons cannot be reconciled with intensity measurements made at high altitudes. In such a case few electrons would be ejected from atoms in the outer regions of the atmosphere by the penetrating photons. Most electrons would be produced at a lower level where the atmosphere is more dense and more photons are absorbed. Bearing in mind the fact that most of the ionization produced in the electroscopes used is caused by electrons rather than by photons, it is clear that on the above assumption the ionization observed should increase with altitude up to a certain point, and then decrease as the instruments are carried higher, having a maximum value at a definite altitude which is not beyond the reach of sounding balloons.

Such a result is not in accord with the observations. All high altitude observations so far made agree that the ionization increases with altitude, the rate of increase falling off as the upper limit of the atmosphere is approached, but never becoming a decrease.

One is forced to conclude that if the incident beam

consists essentially of photons it must be mixed with secondary electrons, which produce the ionization observed at the highest altitudes. At lower altitudes much of the ionization is produced by electrons ejected from air molecules by the photons, or even by the incoming electrons.

Millikan states that the incident secondary electrons would all be absorbed before reaching the earth's surface, so that any latitude effects should be observable only at high altitudes, before these electrons have been absorbed. For recent computations have shown that electrons liberated in the atmosphere of the earth, and many are liberated in such a way, could not show a latitude effect resulting from a deviation of these electrons by the earth's magnetic field. The thickness of the atmosphere is too small.

Together with his colleague Anderson, Millikan has measured the energy of electrons ejected from air molecules at sea level, using the Wilson expansion chamber. The paths of such electrons are made visible in the chamber. As already mentioned, when the chamber is placed in a powerful magnetic field the paths are curved, the amount of curvature being a measure of the kinetic energies of the electrons. In this way an energy corresponding to at least five hundred million volts has been detected. Electrons having an energy of five hundred million volts would not be able to penetrate the entire thickness of the atmosphere, nor would they show latitude effects. It may also be mentioned that the positive electron was discovered in the course of these and similar experi-

ments, the direction of curvature showing the sign of the charge on the ejected particle.

Such is Millikan's argument. Let us now look at Compton's side of the controversy.

It will be recalled that Compton and his observers detected a clearly defined latitude effect, finding the ionization produced by cosmic rays less intense near the magnetic equator than near the magnetic poles.* The change in intensity appears to come near latitude 35° north or south, measured with respect to the magnetic poles. Previous observers, concentrating their efforts in this and higher latitudes, might easily have missed the effect, as in fact most of them did. Compton also noticed that the latitude effect is more pronounced at higher altitudes.

Compton at once assumed that the latitude effect observed at sea level is evidence of electrons that have come into the earth's atmosphere from outside and have penetrated to sea level. Only such electrons would be measurably influenced by the earth's field. These electrons would require initial energies corresponding to some seven billion volts. The larger part of the radiation observed shows no latitude effect and Compton states that so far as this particular evidence goes the radiation might consist either of photons, or of electrons with initial energies corresponding to at least thirty billion volts. The photon assumption however does not agree with high altitude observations for the reasons previously mentioned, especially in view of the presence in the initial beam of

* More recently Millikan has detected the latitude effect.

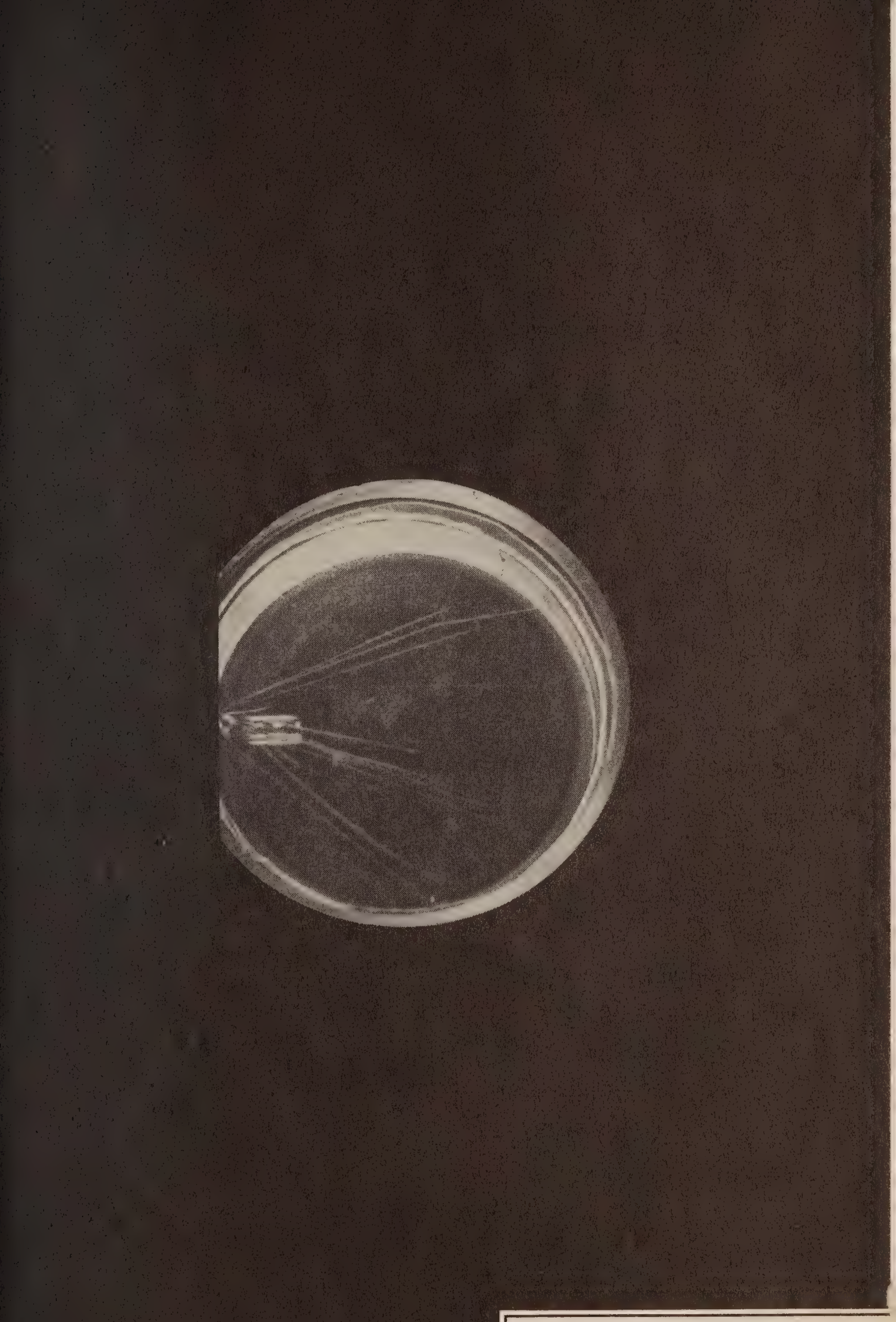


PLATE XIV

The forked path is evidence of a smashed atom.

seven billion volt electrons. Such high energies would never have been imparted to electrons by the impact of photons on air molecules. Millikan had measured much smaller energies for electrons ejected in a similar manner. Secondary electrons approaching the earth with a stream of photons would be deviated by the earth's field so as not to penetrate the atmosphere. If this is the case then a beam of photons, even though initially mixed with secondary electrons, would show the decreased ionization effects at high altitudes which have never been observed.

Thus the controversy continues, although the opinion of the scientific world appears to be tending in the direction of Compton's theory. The subject is attracting an ever increasing number of observers. Some are using electroscopes. Some use a new type of radiation detector that produces a galvanometer deflection or lights a lamp every time a cosmic-ray particle passes the detector. These detectors have been arranged in series, even in banks, so that the direction of the incoming particles can be determined. The fact that more particles are observed to come from the west than the east points to a predominance of positively charged particles, perhaps positrons.

Besides being a question of present day scientific facts and theories the cosmic-ray controversy concerns things of still deeper significance. At the time when Millikan's views appeared to be the most acceptable the cosmic-ray photons were considered by some to be evidence of the continual creation of heavy atoms out of light ones. It is true that several noted scientists

did not agree with this interpretation, and would not give their consent to the view that Millikan's observations were evidence that the Creator was "still on the job." On the other hand Compton's results are in good agreement with a recent theory of Lemaître and Vallarta, which is based on the assumption that cosmic rays were given off when the building of the universe began, that this radiation has been drifting around in space ever since, and has only now reached us. This theory of course contains the germ of decay, for if it is to be accepted all the evidence points to an original and rather sudden occurrence that is not supposed to continue or to be repeated.

In the meantime theory waits upon experiment. Further study of the ionization produced in a portable electroscope or other form of counter may ultimately reveal no one knows what important secrets, and will probably have a further word to say concerning the history of the universe as well as its future. To a greater extent than ever before we study the atom in an attempt to comprehend the entire cosmos. By observing the motion of a tiny electroscope fiber across a microscopic scale man may thus become able to learn a little more about his origin and destiny.

The New Age of Chemistry

CHAPTER XII

BACKGROUND

In the beginning science arose to fill utilitarian needs. The history of every branch of science commences with a few simple discoveries of a practical and useful nature. Only after applied science has reached some degree of completion does pure science become possible.

Although pure science has been a growth from an earlier applied science it has completely outstripped its predecessor. Nowadays applied science leans almost entirely upon pure science, and would be helpless without it.

The truth of this statement becomes apparent on examining the different scientific fields.

Mathematics and especially mathematical philosophy has reached a stage where it can hardly be classified even as a pure science. It has become an art. This present stage is very far removed from that of the early days when man was learning to count and to distinguish in his conversation between two objects and four objects, or even the much later stage when the simple requirements of barter between savage tribes led to methods of calculation which were a distinct advance over the first primitive arithmetic.

When early men had at last left their caves, wandered over the face of the earth, and begun to settle

down in civilized communities, the necessity for establishing the boundaries between the landholdings of neighbors demanded elementary rules of surveying, and geometry was invented. Only later was much interest shown in mathematical demonstration of the general truth of theorems, or in the discovery of theoretical laws of a fundamental nature.

Astronomy, oldest of the natural sciences, had its beginnings in the simple visual observations of the altitude and azimuth of the sun, the phase of the moon, and the position of the sun with respect to the stars, observations which indicated the time of day, the season of the year, and even the time to plant grain or to prepare for floods. This simple knowledge was later extended to enable travelers by land or sea to judge their position with some accuracy. Observations of the positions of the planets gave rise to astrology, that pseudoscience which still thrives vigorously in some quarters. These wholly utilitarian developments preceded the purely scientific aspects of astronomy, such as determination of the distances of the sun, moon, and planets, and attempts to describe and explain the motions of the heavenly bodies.

The situation was no different for the science of physics.

Perhaps the first physical discovery ever made by a human being was that by using branches of trees as levers, larger stones could be lifted and moved, and with less effort.

Many interesting chapters in the recorded history of the human race have been written about the man-

ner in which such primitive discoveries, discoveries pregnant with many of the developments of modern science, came to be made. Were all of them accidental in the first place? Were they the result of observing some natural occurrence? Or were they the result of conscious reasoning?

It has been conjectured that some primitive man, seeing fires set by lightning and feeling their heat, and having noticed that heat resulted from friction, consciously attempted to prepare a fire by rubbing dry sticks one upon another. Perhaps in a similar way the lever was discovered when a hunter stepped on one end of a fallen branch which was resting across a stone, and noticing how easily the boulder lying across the other end of the branch beyond the fulcrum was lifted by the light pressure of his foot, proceeded to adapt the lever to his own uses.

As the centuries passed, men learned how to design hurling engines for use in battle, engines for moving heavy loads across the land, and engines for lifting water, all implements for increasing man's natural physical ability. Only later came the questions put in true scientific fashion, some still unanswered: What is light? What is heat? What is force? What is matter?

Primitive chemistry was at first indissolubly connected with primitive medicine, and here again the first developments were of a practical, utilitarian nature.

Some animals appear to know that the pangs of illness can be relieved by eating certain leaves and

plants, and it can safely be assumed that our prehistoric ancestors possessed the same sort of knowledge. The first chemists were those who learned to prepare these plants and herbs for medicinal use. At first the herbs were merely steeped in water and the brew drunk as medicine. Later it became possible to extract and concentrate the juices. Practitioners of this very useful art were called alchemists.

The field of the alchemists eventually widened. They are most famous for their fruitless search for such things as the elixir of life, a universal cure for all human ills, and for the secret of transmuting some of the baser metals into gold.

Although at this stage in the history of chemistry the search for the secret of transmutation was made for utilitarian purposes and guided by utilitarian motives, intimations of the methods of pure science began to appear.

It was believed at the time that all matter was composed of four elemental substances: earth, air, fire, and water. Each element had its characteristic attributes, derived from four supposed fundamental qualities: hotness, coldness, wetness, and dryness. Fire, for example, was hot and dry. The alchemists thought that by altering the proportions of these qualities in a substance they might be able to change it into some other substance having a different combination of the fundamental attributes and hence different physical and chemical properties. That centuries of alchemy failed in these respects is well known. The wrong choice of fundamental elements precluded suc-

cess. The objectives of the alchemists, as well as some of their methods, were however handed on to the chemists. Unscientific as alchemy was, it became in fact the forerunner of modern chemistry.

The awakening of chemistry occurred at very nearly the same time as that of astronomy and physics under the hands of Galileo and his contemporaries. A sign of the times is the publication by Boyle, who is remembered chiefly for the discovery of a law relating the pressure and volume of a compressed gas and called Boyle's law, of The Skeptical Chemist, wherein doubt was cast upon the vague philosophical pronouncements of the alchemists. Boyle's measurements on the expansion of gases brought clearly to his attention the need for precise measurements and exact scientific statements. He saw the necessity for chemistry to become scientific.

Just as caloric played an important rôle in the history of physics and especially in the development of the theory of heat, so did phlogiston have its important place in the history of chemistry.

Caloric corresponded to what is now recognized as heat energy, which is really a kinetic energy of atoms and molecules. Since heat was not known to be a form of energy until about eighty years ago, caloric was perhaps as good a name as could be chosen. In line with philosophical and scientific thought of the time, caloric was considered to be a "subtle substance," a sort of intangible material substance which entered bodies when they were heated, and passed readily to cooler bodies in contact with a hot body. In processes

of heat transfer a sort of conservation of caloric was recognized, corresponding to some extent with modern ideas of the conservation of heat energy in such processes. Modern scientists have the distinct advantage of being able to trace the changes of heat energy into other forms, such as mechanical energy, and vice versa. Caloric could not be changed into anything else.

In a similar way phlogiston was considered to be a subtle substance, something that escaped from a body when burning, making burning possible. Bodies such as charcoal which were supposed to have a great deal of phlogiston would burn readily. In the oxidizing of metals phlogiston was assumed to be given off and heat developed. In the reducing of the oxides with charcoal, phlogiston passed from the charcoal to the oxide, changing the oxide back into the metal. The term oxide was of course not used during the age of phlogiston, for the entrance of oxygen on the scientific stage was contemporaneous with the exit of phlogiston.

No doubt the concepts of caloric and of phlogiston played an important part in the development of science. Both demanded measurement and experimental manipulation, processes that not only led to the training of men in the use of the experimental method, but as well kept active in their minds the idea of investigation. Only an unchanging world is a dead world. Researches on the flow of caloric and phlogiston led naturally and inevitably to thermodynamics, and to

the discovery of oxygen and an understanding of the process of oxidation.

Much attention was paid to the preparation and examination of gases, or as they were called at the time, airs. Hydrogen, which does not support combustion but which burns in air, was called inflammable air. The gas that Priestley prepared by heating an oxide of mercury was called dephlogisticated air. This is the gas that we call oxygen. It was found that this air or gas supported combustion, and that animals were able to breathe and live in a chamber filled with it. Such were the tests available at the end of the eighteenth century for studying the properties of a newly-discovered gas.

Perhaps more important for the development of the science of chemistry was another discovery of the same period, that of the usefulness of the balance. The name of Lavoisier is especially remembered in this connection.

To a modern scientist, the attempt to understand chemical changes without the use of a balance would appear to be founded on the most forlorn of hopes. The same is true of other fields of investigation. For example, in the early days before the balance was extensively used, an experiment was conducted to determine how a growing plant obtained the material needed for its growth. A tree planted in earth in a tub was watched as it grew. From day to day water was added to the earth, and it was concluded that the material used in the growth of the tree came ex-

clusively from the added water. The use of a balance would have shown at once that the increase in weight of the tree was greater than the weight of the added water. Only much later was it found that carbon dioxide from the air was absorbed by the leaves of the tree in the process of photosynthesis, the carbon thus obtained making up a considerable part of the added weight of the growing tree.

In the same way the use of the balance would have shown at once, as it now proceeded to show, that something was wrong with the phlogiston theory. Carbon, for example, was supposed to lose phlogiston when burned in air. But the balance showed that in the burning, the products of combustion weighed more than the original carbon. This observation spelled the doom for phlogiston, for even such a subtle substance could not be conceived as having a negative weight.

It was due to the use of the balance, now perhaps the principal tool of the analytical chemist, that the difference between physical mixtures and chemical compounds came to be recognized.

A mixture of let us say salt and sugar can be prepared in any proportions whatever. Equal parts can be mixed, twice as much sugar as salt, or in fact any other amounts. The same is not true of the elements in chemical compounds.

Salt is composed of sodium and chlorine, and sugar of carbon, hydrogen, and oxygen. The balance proceeded to show that in salt the two materials sodium and chlorine are always present in the same relative amounts by weight. If excess sodium were added to

the vessel in which salt was being prepared it could not be utilized, as would be the case if the salt were a mixture and not a chemical compound. The same sort of law was found to hold for every chemical compound.

Much of this pioneer analytical work was performed by the illustrious John Dalton, who expressed his results in the now famous law of multiple proportions: Chemical elements combine with each other in relative amounts which are definite and always the same. As a result of such work Dalton was led to the idea of the chemical atom.

It will immediately be seen that Dalton's idea of the atom was to a degree erroneous. The concept of the chemical atom was, however, a distinct step forward. According to this conception one atom of sodium could combine with one atom of chlorine to form one atom of salt. In such a way was the law of multiple proportions explained.

The only trouble with this idea was that it did not distinguish between the atom and the molecule, a failure which did in fact lead to contradictions that Dalton was unable to clear up, but which soon yielded to the investigations of Avogadro.

Avogadro had become especially interested in the chemical reactions of gases, and it was in this field that the molecule as distinct from the atom first became a definite concept.

When gases react chemically there is always a simple numerical relation between the volumes of the gases entering the reaction and of the gaseous products of the reaction, just as there is a definite and simple

relation as expressed by Dalton's law of multiple proportions between the relative weights of reacting substances. For example, one volume of hydrogen and one volume of chlorine can be induced to react chemically. The product is two volumes of hydrogen chloride. The chemist would write, for the reaction: $H_2 + Cl_2 = 2HCl$. One molecule of hydrogen units with one of chlorine to form two molecules, not one atom as Dalton would have said, of hydrogen chloride gas. Avogadro corrected the statement by introducing the molecule.

Thus it became apparent that gases usually exist in the form of molecules. A molecule of hydrogen contains two atoms, and the same thing is true of oxygen. Only a few gases, such as the rare atmospheric gases, helium, argon, etc., which are chemically inert; mercury; and certain gases when under extreme conditions of temperature and pressure; exist in the monatomic state. The law of Avogadro, stating that equal volumes of gases under the same conditions of temperature and pressure contain always the same number of molecules, has become one of the most useful generalizations in the field of chemistry.

The establishment of the chemical atom and molecule date from the early part of the nineteenth century. From the same period comes one of the first of many important achievements in the field of organic chemistry.

In earlier times chemical substances were divided into two groups, the living and the nonliving, or the organic and the inorganic.

It had been believed that only living forms could produce organic substances, especially organic substances under the original definition of living substances or substances produced by living organisms. But during the time when Dalton and Avogadro were laying the foundations on which modern chemistry was to be built, Wöhler succeeded in synthesizing the organic substance urea from inorganic materials.

As knowledge has grown and it has been discovered that most if not in fact all living forms contain carbon, organic substances have been redefined as compounds that contain this element. Under the new classification, acetylene becomes an organic compound and the subject of study for organic chemistry. The same is true of such substances as petroleum and coal tar derivatives.

The triumph of Wöhler was the initial step in a long series of successes which some hope may eventually terminate in the artificial production of living protoplasm. It was at any rate an important landmark in the development of organic chemistry for since then many organic substances have been synthesized in the laboratory, including not only various carbon compounds which would have been considered inorganic under the old classification, but also substances which are important to forms of life and are produced by them.

In the latter half of the century came the all important periodic table of the chemical elements arranged by Mendeleeff which has led to the discovery of many new elements and to the knowledge that only

a finite number of these elements, about ninety in fact, can exist on earth. The usefulness of this classification for physics and for the study of atomic structure has been mentioned in a previous chapter. Here need only be recalled the concept of atomic number, a number equal to the net charge on the atomic nucleus, which has given a criterion for the correct arrangement of the elements in the periodic table; and the concept of isotopes, chemical elements that have different atomic weights but the same atomic number, nuclear charge, and chemical properties.

As the body of chemical knowledge grew, it became apparent that certain compounds having the same chemical elements in the same proportions did not always possess the same chemical properties. Such compounds are called isomers.

As examples of organic isomers we may consider:

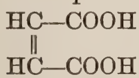
$C_2H_5—O—C_2H_5$	$CH_3—O—C_3H_7$
diethyl ether	Methyl—propyl ether

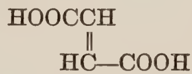
Both have the general formula $C_4H_{10}O$.

It was soon found that the differing chemical properties of such substances depended not only on the elements present, but on the actual structure of the molecules. For two reasons molecular structure becomes especially important in organic compounds: Organic molecules are extremely complex, and sometimes contain hundreds of atoms. Also, it is a property of carbon atoms to unite in long chains. This very property in fact accounts for the multiplicity and complexity of organic molecules, and of all the substances necessary for life processes.

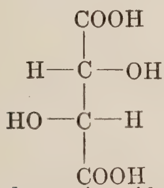
How are these molecular structures discovered? Chiefly by examining the way in which these compounds are produced, or the ways in which the substances combine with other substances. Part of the complex molecule can be split off and combined with other substances. An analysis of the new compound will then give an idea of where the original molecule split.

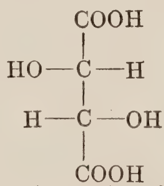
More complex examples are:


maleic acid

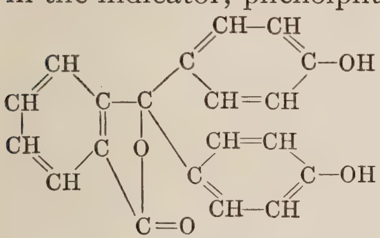

fumaric acid

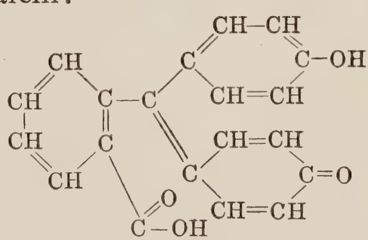
The lines in each case represent chemical bonds.


d-tartaric acid


l-tartaric acid

Even color may depend on molecular structure, as in the indicator, phenolphthalein:


Colorless


Reddish

In some cases the mechanical structure of crystals is of service, and the effect of a substance on a beam of polarized light often gives information. For example, a solution of d-tartaric acid rotates the plane of polarization to the right, while l-tartaric acid rotates it to the left.

The structures shown are according to Kekulé, and are widely but not as yet universally accepted.

An application of the physical methods of x-ray analysis of crystal and molecular structure has also been useful in this connection. Not only have the plane structural arrangements of atoms been determined, but also the space arrangements. The way in which this new body of knowledge has been turned to use in understanding molecules and their structures, and in learning how to synthesize these same molecules and also new molecules designed for special purposes, will presently be discussed. Knowledge of the methods of organic chemistry has opened new fields to the biochemist, and has produced new reasons for hoping that sometime the processes of life will be understood with completeness. If the day ever comes when protoplasm, the life substance in living form, can be produced from nonliving substances in the chemical laboratory, the organic chemist will have been responsible for the accumulation of knowledge making this discovery possible.

CHAPTER XIII

A USEFUL SERVANT

In his autobiography Andrew Carnegie tells of his experiences in the early days of the steel industry. Metallurgy was then less of a science than an empirical art based on rule of thumb.

According to Carnegie's story, one kind of iron ore obtainable at the time gave particular trouble in the smelting process, so much trouble in fact that the price of the ore fell far below that of other ores which gave better results. The smelting process, as has just been mentioned, was based on certain rules that had no other justification than that they had been used before. All ores were treated in similar fashion: so much ore, so much fuel, so much flux.

The thought occurred to Carnegie that this condition was not entirely satisfactory. Might it not be true that ores differed, that some were richer in iron than others, and that the smelting process should be adapted to suit each individual ore? Accordingly, against the advice of some of his associates, and to the derision of many of his competitors, he employed a chemist and established a chemical laboratory on the premises, so that the constitution of his ores could be tested. It soon appeared that the difficulties with the unsatisfactory ore were traceable to its very richness. The greater iron content of this ore, combined

with the accepted smelting technique, had led to such troubles as clogging of the furnaces.

A trial run of the furnaces with the supposed poor ore, but with less fuel and flux, gave a complete vindication of the chemist's findings and of Carnegie's revolutionary procedure in establishing his chemical laboratory: more iron was obtained from the ore than from any of the other ores. Acting on this information, he proceeded to buy large quantities of this rich ore, which he could still obtain at a low price. His competitors were not slow in adding chemical research laboratories to their own establishments.

It is a far cry from these earlier days to the present, when every large industrial plant has its research laboratory well stocked with scientific instruments and staffed with trained investigators. Steel, gasoline, dyes, illuminating gas and most of the other products used in this industrial age are produced under the skillful guidance of the chemist, the physicist, and the geologist. Even the mathematician is not forgotten.

In this chapter will be discussed some of the recent industrial successes that have resulted from the wedding of chemical research to industry, successes that have made possible products of a quality and inexpensiveness unknown in earlier days.

The development of industrial chemistry has been somewhat different from the development of many new industries dependent on physical discoveries. A few examples will serve to illustrate the point.

One of the most important present-day industries is communication. Telegraph, telephone, and radio

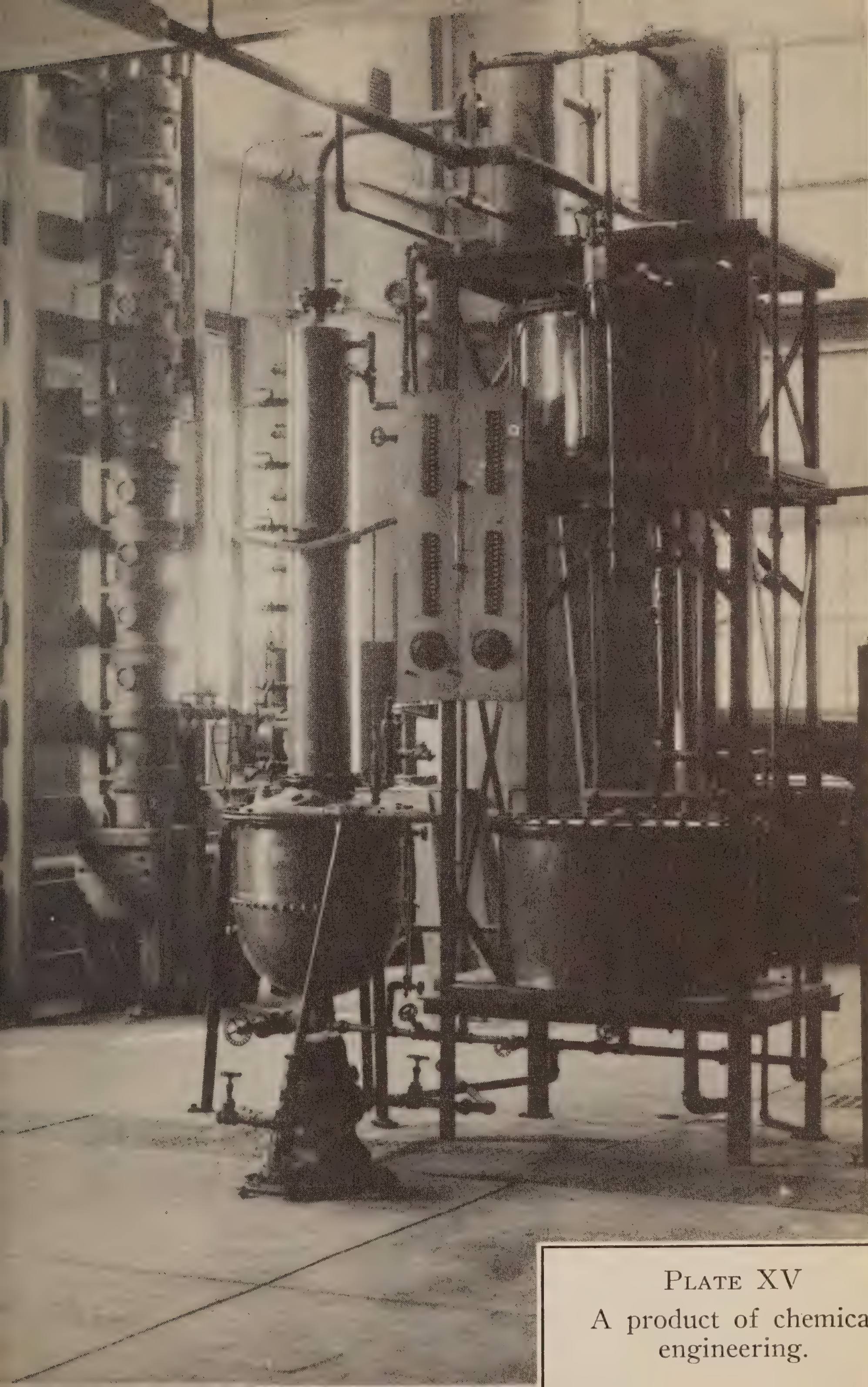


PLATE XV
A product of chemica[l]
engineering.

link together the widespread parts of the world. Soon television will join them even more closely.

Morse's telegraph was the first means of sending intelligible signals over a wire by means of electricity. The possibility of doing so had to await the invention of the electromagnet. The telegraph would have been unthinkable without this instrument of science presented to the world by Henry, Faraday and a few of their contemporaries. The telephone is also dependent on the electromagnet, as well as on other physical discoveries dating from the same period. And the radio became possible toward the end of the last century when Maxwell predicted the existence of electromagnetic waves and Hertz produced and measured them. Just before the work of Maxwell and Hertz the radio telegraph was an impossibility. Immediately afterward when radio waves had already been sent over short distances, the time was ripe for a Marconi to use his engineering genius to work out the practical details.

But as has been mentioned, the developments of industrial chemistry have been somewhat different.

Many chemists are employed today in the manufacture and experimental study of fertilizer. Naturally it cannot be claimed that at any given moment in history it became possible to make and use fertilizer. Crops were grown in very ancient times, for one of man's first capabilities was tilling the soil. The origin of agriculture is so remote that history begins after agriculture had become an art. Even primitive people know that certain soils are more suited to

specific food products, and that poor soil can often be made more productive by adding manure. Agriculture has grown slowly by processes of trial and error, new discoveries such as the advisability of the rotation of crops being used without understanding the processes involved, or knowing the reasons for them.

To a man of the present day, steeped in all the scientific lore that is our modern heritage, it would appear that the relation of the chemist to the science of agriculture should be a very definite one. The chemist analyzes the materials used as fertilizers and also the soil and the food products grown therein, and determines the reasons for using manure and the quantity desirable, so that the process used for so many years as a rule of thumb may at last be understood.

But in this, as in other arts and crafts that have grown up with the ages, the chemist has not found universal appreciation of his services. The secrets of agriculture have often been passed from father to son for so many generations that it has been difficult to impress the farmer with the practical importance of things happening in the chemist's test tube—things that often result, once the effects observed in the test tube are put into practice, in doubling or tripling the yield of crops per acre.

In many cases the application of chemistry to industry has resulted in new ways of doing things already known—better, more efficient and less expensive ways. With the introduction of research chemistry into the steel industry by Carnegie, steel became

not only cheaper but better. The desirability of controlling industrial operations in a scientific manner has finally been recognized to so great an extent that not only the industries themselves, but the governments as well, spend vast sums on experimental research. In America the Bureau of Standards is equipped to calibrate measuring devices, and to perform fundamental researches that have proved of inestimable benefit. The department of agriculture is continually assisting the people of this country by the publication of its researches relating to soil chemistry, fertilizers, and the utilization of farm wastes.

Often, however, industries have been founded as the result of chemical researches. Aluminum, perhaps the most important metal of the immediate future, was obtainable only at prohibitive expense before chemists learned to prepare it by the modern electrolytic method. Nitrates are produced cheaply from the air, helium from natural gas, and rayon yarn from cellulose, all as the result of chemical researches.

Let us look, for example, at nitrogen. About four-fifths of the atmosphere consists of nitrogen as a gas, serving to dilute the oxygen that we breathe. But as a source of nitrogen compounds in a form capable of utilization whether as fertilizers or explosives, atmospheric nitrogen has until recently been practically useless.

For years nitrates were obtained exclusively from mineral deposits, most of which were in Chile. This condition was far from satisfactory, except possibly to the present owners of the deposits of saltpetre,

the nitrate beds, who were able to profit by their monopoly. In the first place, the supply is limited. It was predicted some years ago that the supply would have been depleted even before the present. Although there is still a quantity of unmined nitrate in Chile and elsewhere, the supply is not inexhaustible, and will sometime in the not too distant future become extinct. What would a world dependent on these beds for its supply of nitrates do then? In the second place, no nation considers it a satisfactory state of affairs when some other nation controls the world's entire supply of some indispensable product.

Necessity proved in this instance as it has in so many others to be the mother of invention. Here was the need for nitrates, and there was the nitrogen in the air. The challenge to the chemist proved irresistible.

Nitrogen is now obtained in usable compounds from the atmosphere, or as the chemists say, is fixed, in three ways: oxidation of nitrogen by means of a powerful electric discharge, the oxide formed being altered and combined with suitable chemicals to adapt it to use as a fertilizer, or in the explosive industry; by the cyanamide process; and by direct union with hydrogen in the presence of a catalyst to form ammonia, which in turn can be changed or combined with other substances to form nitric acid and nitrates.

It has been known that from nitrogen in the atmosphere chemical compounds such as ammonia were formed by the action of lightning. It has also been known that certain bacteria, present in the soil, were

able to cause the fixation of atmospheric nitrogen and its combination with other substances. These bacteria occur with the roots of such agricultural products as peas and beans. Accordingly, these vegetables are planted first in one section of a garden then in another, in order to replenish the supply of nitrogen in the ground which is depleted by most growing things, and necessary for the growth of protein. Decaying animal or vegetable material containing protein is also a source of nitrogen compounds. The presence of nitrate beds, referred to above, is due to these causes, principally the third. Ammonia, a compound of nitrogen and hydrogen, can be prepared by the distillation of animal products, such as hides and horns.

None of these sources of nitrogen compounds, save only the nitrate beds, have until recently been able to supply combined nitrogen in anything like the quantity needed in industry.

A few years ago the most promising method for the fixation of atmospheric nitrogen appeared to be an adaptation of the natural process occurring in thunderstorms. A powerful electric discharge was passed through atmospheric air, causing the oxidation of the nitrogen. This oxide was then combined with oxygen to form a higher oxide, thus becoming suitable for the production of nitric acid and the nitrates, or else it was combined directly with certain salts which became usable as fertilizer. This method of fixing nitrogen from the air was of course dependent on the availability of large sources of electric power. It was developed in Norway, where water power is

plentiful, and later in other countries. In America, the hydroelectric plant at Muscle Shoals was originally designed to serve as a nitrogen fixation plant, and would have been so used had not the war ended when it did. During the years since the war, while the Muscle Shoals plant has lain idle, newer and better methods have been developed for the fixation of nitrogen, so that the use of electric power is now too expensive in view of the cheapness of the newer methods.

For the manufacture of fertilizer the cyanamide process has been found to be inexpensive and satisfactory. The method depends on the use of calcium carbide, a substance long known and used in the production of acetylene. The convenience of this use of calcium carbide, requiring only the addition of water to form the gas once used extensively as an illuminating gas, not only in buildings but for automobile headlights as well, explains its development and manufacture.

Calcium carbide is prepared simply and cheaply by heating together coke and lime. By passing a stream of air over the hot carbide, calcium cyanamide is produced, a substance containing nitrogen, which is well suited for use as a fertilizer, the nitrogen being given off slowly in soluble compounds that can be used by growing plants.

The third method of preparing nitrogen compounds, the most recently developed, the cheapest, and perhaps the method destined to be the most important during the coming years is the direct combination of atmospheric nitrogen with hydrogen to form am-

monia, which can in turn be changed by proper chemical processes into nitric acid and nitrates.

In this method, nitrogen is obtained from the air free of oxygen by liquefying the air and allowing the liquid to evaporate. Since nitrogen has a lower boiling temperature than oxygen, the nitrogen will boil away first, and can be collected as a comparatively pure gas. The oxygen that is left, and boils away last, can be purified and sold in commercial tanks.

Nitrogen then is mixed with hydrogen gas and caused to combine with the hydrogen by means of a catalyst. But what is a catalyst?

A very graphic explanation of what a catalyst is has been given by Swann, who by the way is more of a physicist than a chemist. Here is the story:

An Arab tribesman who was on the point of death called in a dear friend and made arrangement for the disposition of his estate, consisting of seventeen camels, to his three sons. The eldest was to have one-half of the estate, the second one-third, and the youngest one-ninth. Making a rapid mental calculation as to what a half of seventeen might be, the friend was about to ask for further instructions, but the tribesman's strength was spent. He expired without giving the desired information.

The friend, unable to solve the question that still vexed him, sought the advice of a very wise and learned man who promised to be of assistance.

"Allow me to loan you a camel," said the wise man. "Then you will have eighteen camels, and a half of eighteen is nine."

"So be it," replied his questioner, who accepted the

loan of the camel, and proceeded with the division of the estate. One-half of eighteen, or nine, camels were presented to the oldest son. One-third of the estate, or six camels, were given to the second. And one-ninth, or two, fell to the lot of the youngest.

Whereupon the executor exclaimed, "Behold, I have divided the estate, and I still have the one camel left. Allah be praised!" Whereupon he returned the camel that had been borrowed.

In the words of Swann, the borrowed camel was a catalyst.

In chemistry a catalyst is a substance which assists a chemical reaction to take place, or causes it to proceed with greater rapidity, without itself entering into the reaction. Such substances have long been used in chemistry, but recently great strides have been made in the use of catalysts, especially catalytic surfaces. Some of this work will be discussed in the next chapter.

Iron was one of the first catalytic substances used in promoting the union of nitrogen and hydrogen, but other and more suitable substances have since been developed. One of the most desirable properties of a good catalyst is that it shall be immune from catalytic poisons, substances which even in extremely minute amounts will ruin the catalytic action of the substance or surface.

Once ammonia has been produced, it is a simple matter to convert it into any one of many useful compounds suited for the purpose at hand, whether it be for fertilizer, for the manufacture of explosives, or

for any other uses that industry may find for these compounds. Fixation of nitrogen in this way is by far the cheapest method available, and promises to be widely used in the immediate future.

While some chemists have been intent on the production of nitrogen compounds from the atmosphere, others have been just as busy in a different field.

The present age has been called the age of electricity, and even the age of science. The implication that this is the great age of either is not intended, for no one is able to foresee what the future has in store, and further developments will surely transcend anything that is at present known to science. But it is true that both the application of electricity and the development of science are proceeding at a pace which would leave men of a generation or two ago quite out of breath. Much of this rapid development has been made possible by progress in the refining of metals and in the production of new alloys designed for special purposes. A chemist would not go far wrong in calling the present the age of metals.

Today the most important metal, without exception, is iron. The machines and tools of production are made almost entirely of iron and steel. Skyscrapers, great bridges, railroad tracks and rolling stock, farm implements, and many other useful articles are made wholly or partly from this metal. What has the chemist done to bring all this about?

The smelting of iron from the oxide and sulphide ores which occur in nature was practiced long before the entrance into industry of the research chemist,

just as glass was made centuries before the making of glass was well understood from a scientific point of view. Some would have it that the discovery of glass dates from the time when some primitive man noticed a transparent substance oozing from his campfire built upon the sands of a beach. Whether this is true or not, it is certain that products of such perfection as pyrex and optical glass, products made under careful chemical control, far transcend any of the crude window glasses made before the scientific era. Carnegie had shown the great gain in economy and efficiency that results from the introduction of chemical control into the iron and steel industry. From the proper control of the blast furnace, which was Carnegie's initial contribution, to the era of stainless steel and permalloy is indeed a long step, a step whose foundations have been laid and kept in repair by the chemists.

Iron offers a variety of opportunities. By means of the addition of a very small percentage of other substances and the proper treatment, it can be made hard or soft, tough or brittle. It can be made into suitable material for high speed cutting tools for production machinery, or into stainless steel for table cutlery. It can be made to have almost any magnetic qualities desired. Without the services of the chemist much of the usefulness of iron would be unavailable, for the minute quantities of other elements that give to steel its properties could not be regulated by any but scientific means. No hit-or-miss or rule-of-thumb method would be adequate.

In spite of the present supremacy of iron and steel,

the building material of the future may very well turn out to be one of the light aluminum alloys. One such alloy, duralumin, has already found extensive utilization in the construction of aircraft. The time may soon come, after chemists have discovered still cheaper ways of producing this metal than the present electrolytic method that made aluminum available at a moderate cost, as well as new alloys having greater strength, when many of the uses of steel will become uses of aluminum.

The chemist is ever on the search not only for cheaper methods of producing such useful substances as steel and aluminum, but as well for new materials that will be of even greater service to humanity. It has been but a short time since commercial products were first plated with chromium, but now nearly every automobile has some of its exterior plated with this shining metal which lasts so much longer without tarnishing than nickel plate. Chromium has entered the kitchen on electric toasters and waffle irons, taking its place beside the aluminum pots and pans which have been made practical for domestic use and available at low cost by the work of the research chemist.

Probably the first fuel used by primitive men was wood, although petroleum may have been utilized to a slight degree. If the first fire was copied from a natural conflagration resulting from a flash of lightning, it may have been petroleum, flowing to the surface, that was ignited. Petroleum could not have been used to any great extent, for very little of it is obtainable on the earth's surface, whereas wood is al-

most everywhere. Peat has also been used as fuel from very early times, and coal from times perhaps not quite so early.

For years coal was by far the most important fuel used in industry. Its use grew with that of iron and steel, the three furnishing in a very literal sense the backbone of the industrial revolution. Coal has been used for the production and purification of iron, as well as the production of steam for industrial use. The very development of the American continent depended on coal, and in the great era of railroad building coal was almost the sole source of power for transportation over land.

Today we are in quite a different situation. For in the meantime petroleum products have become of the greatest importance as fuels, whether for industrial use, domestic heating, or for transportation. And what is more to the point, the chemists are finding important ways of conserving these products, both by improving the efficiency of heating processes, and by discovering ways of greatly increasing the available yield of fuel substances from the crude petroleum occurring in nature.

The modern chemist is more interested in petroleum than in coal as a fuel, for coal has become to the chemist the source of a long list of coal tar products, dyes, explosives, perfumes, and what not. Coal tar products will be discussed shortly.

The petroleum industry is one of the largest and most important industries in America. This country is a leader not only in the consumption of petroleum products, but also in their production.

Petroleum in itself is not very useful, containing as it does such volatile and inflammable substances as gasoline and kerosene, as well as such substances as petroleum jelly and paraffin. These substances, nearly all hydrocarbons consisting of carbon and hydrogen in different proportions, can however be separated one from another and made available for the use to which each one is suited.

As petroleum is heated the more volatile substances, which happen to be those consisting of the lightest and simplest molecules, evaporate first. In this way gasoline, among the early products of the distillation process, is obtained. At higher temperatures heavier products are evaporated and collected, such as kerosene and light lubricating oils. At even higher temperatures are obtained the heavy lubricating oils. The residue left in the still contains paraffin and petroleum jelly, the latter marketed under the trade name vaseline. The separation process is called fractional distillation, and each product is called a fraction. Sometimes the distillation must be carried out more than once, in order to separate the fractions with the desired degree of purity.

What place has the chemist in this important industry? It will be clear that the success of the distillation process depends on careful control, as well as knowledge of exactly which of the hydrocarbons come off at a given temperature, a knowledge which can only be obtained by an analysis of the crude oil to be distilled and of the distillation products. But this is not all. Chemists have developed the so-called cracking process, by the use of which the yield of gasoline

is more than tripled. For in this age of motor transportation gasoline has become the most desired petroleum product.

When the heavier fractions from the distillation of petroleum are heated to a high temperature under considerable pressure the heavier, more complicated molecules of these higher fractions break up to form more simple and lighter molecules, such as those of the products present in gasoline. Without this method, developed in chemical research laboratories, gasoline would have become by now a product scarce and expensive, and the rapid development of the motor car industry would have been retarded.

There is a growing conviction among chemists that it should be possible to make of the petroleum industry something akin to the coal tar industry, which is about to be described. If present investigations result in the degree of success which is hoped for, we shall find a multitude of industries growing where none were before, manufacturing solvents, dyes, explosives, medicines, and many other useful substances, all from the products contained in crude petroleum.

Coal tar was at one time the bane of the gas and coke industry. It has become, thanks to the chemist, one of the most valued of industrial products and raw materials, and has been the basis for the growth of some of the world's greatest industries.

When coal is subjected to the process of destructive distillation, coal gas is given off and the coal becomes coke, the coal tar collecting in a viscous mass as a residue. It is an unpleasant, foul smelling substance,

and at one time its removal was one of the principal problems of the industry. It can, by fractional distillation, be made to yield such substances as ammonia, benzene, phenol, naphthalene, creosote, and anthracene, leaving a residue consisting of pitch.

These distillation products themselves have recently found considerable use. Creosote, for example, has been found to be an excellent preservative for lumber, and is used to coat the lower ends of telegraph poles and the exposed surfaces of raw woodwork. Phenol is a disinfectant, and naphthalene, another product of coal tar distillation, is used as a disinfectant, and for moth balls. The pitch has found extensive application in road building. These developments alone would have provided a practical use for the coal tar which had formerly been a drug on the market.

In the meantime, however, something else was happening, something which was to alter the entire course of the development of industrial chemistry.

Benzene from coal tar, when properly treated, yields a substance called aniline. About the middle of the last century the chemist Perkin was experimenting with this substance, treating it with this and that chemical reagent, trying to see what could be made from the aniline. He found out, but his discovery was not what he had expected. For what he found was mauve, the first aniline dye.

From the time of Perkin's great discovery the development of the artificial or synthetic dye industry has been phenomenal. It has provided the means for

the growth of great chemical industries, first in Germany, and during and since the war, in other countries. It has resulted in the virtual abandonment of large areas of land devoted to the growth of plants from which dye materials had been extracted, and has given to the textile industry dyes in almost infinite variety. Moreover, since the materials used in the dye industry are in many cases the very substances necessary for the manufacture of modern explosives, and since a factory devoted to the manufacture of dyes from coal tar products can be turned with very little trouble and expense into a factory for the making of these explosives, the development of the dye industry in countries such as ours has resulted in a gain for national defense. Such has been the result of something that happened in a test tube in Perkin's laboratory. Among the useful substances now prepared from coal tar derivatives are numbered, along with the dyes, flavoring extracts, perfumes and medicines.

Not only has chemistry provided new dyes for old substances, but it has as well provided new textile products.

When Mercer perfected the process for "mercerizing" cotton by treating it with concentrated alkaline solutions, a new method for making what was at first called artificial silk was discovered. A more recent form of artificial silk is called rayon, and articles of clothing made from it can be purchased in every country store. Not only is rayon in many cases as durable as silk and as beautiful, but it is much less expensive.

Rayon is made by dissolving cellulose from cotton or even from wood fibers in a suitable solution, then extruding it from small holes into another solution. The extruded streams coagulate, the resulting fibers being collected, spun, and woven into cloth. Rayon is a safe and sane relative of nitrocellulose, a powerful explosive.

These examples will suffice to show man's debt to the research chemist. The waste products of industry or of agriculture have been put to use, with the production of new substances which are both cheaper and better than their predecessors. By-products have in some instances become of greater value than the original products themselves.

The efficiency of some of the processes of modern chemical industry is almost unbelievable. Not only are all the products and by-products utilized, the reagents collected and used over and over. Even the heat and smoke from furnaces have been turned into account. Man has benefited from these processes which furnish him with goods and products of ever greater quality and at less cost.

The work goes on with ever increasing speed. Whether in the hydrogenation of oils in the presence of new catalysts to form solid fats which serve as improved substitutes for lard in cooking, or in the development of microchemistry so that a minute drop of blood can be analyzed to give important clues to the criminologist; whether in the profitable utilization of agricultural waste products, or in the conservation of natural resources by the more efficient use of metals, oils, and ores; the chemists are always at work. They

are continually seeking ways of reducing the human hazards in manufacturing processes, looking for new and nonpoisonous products to replace those whose handling is dangerous, and finding conditions under which dangerous chemicals and gases may be handled without peril to the worker or to the domestic user for whom these substances are produced.

CHAPTER XIV

WHAT NEWS FROM THE FRONT?

It would be unfortunate if a perusal of the preceding chapter should leave the impression that chemistry is at present entirely concerned with the manufacture of cheaper gasoline, or a more serviceable grade of stainless steel.

Of late years the amount of news space devoted to science has been continually increasing, in accord with the growing desire on the part of the reading public for the latest information from research laboratories. And it must be admitted that by far the larger part of this space has been given over to discoveries in the fields of physics and astronomy. Many of the most startling discoveries of recent times have been made in these fields. It is only necessary to mention the successful transmutation of certain of the elements, the conversion of matter into energy and vice versa, and the breath-taking discovery of the expanding universe with all its implications, to realize what new ideas have been presented to the world in the comparatively brief span of little more than a generation.

The news columns have not entirely neglected the field of chemistry, but in many cases the discoveries announced have been of the nature of those described in the last chapter.

While the physicists have gone bravely forward, unravelling the secrets of nature and presenting the world with one fundamental particle after another, working in a field which had belonged to chemistry until it became apparent that further advances demanded the application of physical methods, the chemists have not been idle. For just as the work of the chemist Dalton, and of Avogadro, made possible many of the recent discoveries of the physicists, so have the present discoveries in physics prepared a field of endeavor which is the true hunting ground for the chemist. While the work in practical and engineering chemistry goes onward, chemistry is once more turning its attention toward the search for fundamentals.

Now that physics has given a pretty good explanation of what a chemical atom really is, the chemist is able to go forward with a new study of the processes of chemical combination, with greater certainty than ever that he is on the right track and that perplexing problems will at last be solved.

The physical chemist is a member of a comparatively new species. But he is not out of place in a scientific world containing the biochemist and the biophysicist. The application of physical methods to the problems of chemistry, and vice versa, have indeed proceeded so far that it has become somewhat difficult to classify a man as either a physicist or a chemist. We may be moving toward the stage when all such investigators will be classed only as scientists, just as they were once all included under the general term, natural philosophers.

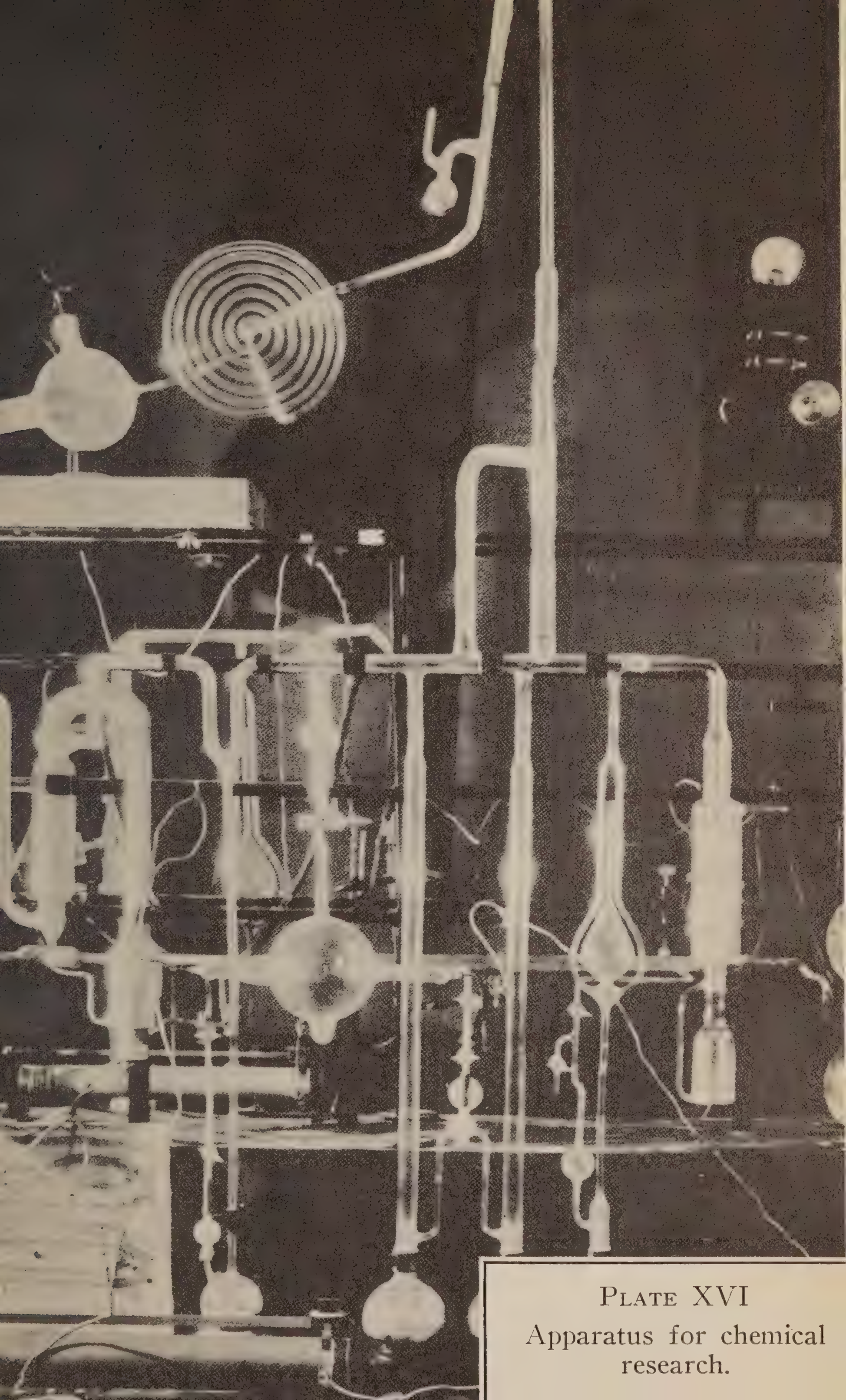


PLATE XVI
Apparatus for chemical research.

The physical chemist is chiefly concerned with a new attempt to understand and interpret the chemical processes which have so long been known. This work is the purest sort of science, as contrasted to much of the chemical work that has already been discussed. But it cannot be denied that success in this new field, as indeed in any field of pure science, astrophysics for example, may end in leading to the most practical of discoveries.

Some modern chemists are just as industrious in another field which is neither strictly pure nor strictly applied science, those who are seeking to make of chemistry a servant of medicine. A discussion of this aspect of chemistry will be postponed until later.

Much of chemical knowledge has been accumulated through the years by the painstaking method of trial and error. That this method can be very productive is shown by the large number of chemical compounds that are now known. If one has time enough, it is quite a simple process to combine two or more known elements or compounds in a test tube, and failing the rare occurrence of a disastrous explosion, to analyze and study the resulting compound. It is even possible, after such knowledge has grown considerably, to predict with some confidence what the result of the chemical reaction will be. For example, once the structure of a certain chemical molecule has been ascertained, it is quite often possible to choose such reagents that their combination will give the desired compound. In this way many of the interesting organic compounds have been synthesized.

But there is a certain kind of knowledge that the old methods will not give. Why, for instance, do chemical elements combine? Why are some compounds so stable, and others relatively unstable? What is the nature of the bond that holds together the atoms of chemical elements making up a molecule? Once these questions can be answered satisfactorily, it should be possible to achieve greater success in the synthesis of desired compounds. Answers to these questions will give the chemist that feeling of satisfaction that has now and then come to the physicist in recent years when he has achieved a satisfactory explanation of atomic structure. For although in recent years the physicist has been pursuing his will-of-the-wisp with greater avidity, the chemist is also concerned about the nature of ultimate reality.

One of the earliest attempts along this line resulted in the very useful concept of chemical valence.

The valence of an atom, or of a group of atoms commonly associated together and entering into chemical reactions as a unit, determines the number of other atoms or groups with which the original one is able to combine. The idea can perhaps be clarified by an analogy: a normal human being might in a sense be said to have a valence of two, for he can shake hands with two separate individuals at the same time. The valence of a person who had lost one arm would according to this very loose analogy be only one. The analogy is far from complete, because the second person could simultaneously shake hands with a third person, he with a fourth, and so on. In chemistry an

atom with a valence of one is able to combine with one other atom at a time, and no more, while an atom or group having a valence of two can combine with two univalent atoms or one divalent atom at a time, and no more. Sodium chloride, for which the chemists write NaCl, represents the combination of two univalent atoms. Sodium sulphate, Na_2SO_4, represents the combination of two univalent sodium atoms with one divalent sulphate group. Both valences of the sulphate group are utilized when the group combines with the two sodium atoms. All the chemical bonds are in use, and it is impossible to force another atom to combine with the molecule of sodium sulphate. By displacing one of the sodium atoms, such a compound as $NaHSO_4$ can be formed, in which one sodium atom has been replaced by a univalent hydrogen atom.

The concept of valence goes a considerable way towards explaining, or perhaps better, enabling one to understand the nature of chemical bonds. It certainly does give to the chemist a very useful tool, in much the same way that the discovery of electricity gave to physicists and engineers a tool that could be and was used for many years before electricity was at all understood. The concept has been of especial use to the organic chemist intent on the analysis and synthesis of complicated organic molecules, and has led to a comprehension of the structure of molecules, and of isomers, mentioned in a previous chapter. But it does not go far enough to satisfy the chemist who is searching for reality and for a truly scientific and

complete understanding of the forces binding atoms together into molecules.

Different chemical reactions proceed at different speeds. If all reactions were slow we would probably still be arming against our enemies with bows and arrows, for there would be no explosives. If on the other hand no reactions were slow, the span of life would be shorter. Life under such circumstances would be very difficult indeed, the ordinary processes of peaceful living being continually disturbed by unexpected and violent explosions.

It was early recognized that the speed of a chemical reaction might give important information concerning the nature of the processes of chemical combination, and of the chemical bond.

In studies relating to the speed of chemical reactions, catalysts play an all-important part.

A catalyst, as has already been explained, is a substance that initiates, or assists the completion, or increases the speed of chemical action without itself taking part in the reaction. For instance, a catalyst is necessary to bring about the direct union of nitrogen and hydrogen to form ammonia. Many reactions that are certainly catalytic in character take place without the obvious addition of a catalyst. The very active substances sodium and chlorine, which under ordinary circumstances will readily combine to form common salt, will not combine even at high temperatures when all traces of water are absent. Different substances are useful as catalysts, according to the chemical

agents present. Iron is often used as a catalyst, and so are several other metals.

The condition of the catalytic surface appears to be of the greatest importance. In the older empirical age of chemistry it was often found that reactions, to be successful, must be carried out in containing vessels of a definite material. The presence of a particular metal, possibly in the form of a cover to the vessel in which the reaction was to take place, would completely inhibit the reaction. Such discoveries, of the greatest practical use to chemical engineering, were nevertheless not entirely satisfactory, since no explanation was forthcoming as to the reason for the observed catalytic action.

It is believed that most reactions which are not instantaneous as well as some reactions which proceed too rapidly for the rate of reaction to be measured are due to some sort of catalytic action. In general it is true that reactions proceed more rapidly in the presence of a suitable catalyst, as if the catalyst caused a weakening of the chemical bonds of the atoms in the reacting molecules. It was suspected that here was a fertile ground for investigating the facts of chemical combination. That this suspicion was well founded will appear in the present discussion.

Such work has fallen to the physical chemist. Physics has given a model of the atom which however far from finality is at least a useful working model, and adaptable to the use of the chemist intent on a study of the chemical combination of such atoms. De-

velopments in this field have followed developments in the physical field of atomic structure. The Bohr atom led to considerable success, while the latest atom model of quantum mechanics has led the physical chemist even farther.

The Bohr atom, an adaptation of the earlier Rutherford atom model, was developed in order to explain the facts of spectroscopy. Its use in physical chemistry has led to the first intimate understanding of the facts of chemical combination.

It will be recalled that the atom model of Bohr is the planetary atom, with electrons moving in orbits around a central positively-charged nucleus. The nucleus is built up of protons, neutrons, and perhaps electrons. It contains nearly the entire mass of the atom. The mass of the nucleus is slightly less than the combined masses of its constituents, the difference appearing as energy of binding, in accord with Einstein's equation relating mass and energy. Knowledge of this binding energy has been useful in experiments on the artificial disintegration of nuclei and the production of neutrons, as has been described. The net positive charge on the nucleus, equal to the atomic number, is what determines the chemical properties of the atom. The electron orbits are determined by the laws of mechanics, subject to the quantum restrictions.

It soon became apparent that a new periodic classification of the elements, differing somewhat from the famous periodic table of Mendeleeff, would be useful in studying the chemical properties of Bohr atoms.

An examination of the two forms of the periodic table shows at once that the new table is based upon the older one. In each the elements follow one another in the same order. Only the grouping has been changed. It will soon appear that the grouping in the new table depends on the arrangement of electron orbits in the atom.

Hydrogen, as known before the discovery of heavy hydrogen or deuterium, consists of atoms having one proton as a nucleus with one electron revolving around it. Such an atom has an atomic weight of very nearly one, and an atomic number of one. The helium atom, next to hydrogen in the periodic table, contains two electrons revolving around a nucleus which is made up of four protons and two electrons. Possibly it contains some neutrons instead. This nucleus has an atomic weight of about four and an atomic number of two. An atom of ionized helium, having lost one electron, behaves somewhat like a hydrogen atom, the only difference being that now the single electron revolves in a more powerful field of force, giving a spectrum which though not identical with the hydrogen spectrum is nevertheless very similar to it. The main point is that the electrons in the atoms of hydrogen and helium are, in the unexcited state of the atom, at about the same average distance from the nucleus.

During the last year or two, since the discovery of the neutron, the constitution of atomic nuclei out of protons and electrons has been questioned. A few years ago, when the chemists were first trying to use

the physical theory of atomic structure to explain chemical facts, the neutron was unknown.

Helium is chemically inert. The next element, lithium, has an atomic number of three, and three electrons revolving around the nucleus. But something has happened in moving from helium to lithium, for although two of the extranuclear electrons in the lithium atom resemble those in the helium atom one moves in a much larger orbit.

Lithium has a valence of one. Beryllium, which follows lithium, has two electrons moving in larger orbits, and a valence of two. It was surmised that the electrons moving in the external orbits might have something to do with the valence of an atom, and about the bonds holding one atom to another.

Moving along the periodic table, through boron, carbon, nitrogen, oxygen, and fluorine, each with one more orbital electron than the preceding, we come to the chemically inert gas neon, having eight electrons moving in larger orbits and two in smaller orbits. The next element, sodium, has one electron in a still larger orbit and a valence of unity. The process continues until argon is reached, having eight electrons in the outer shell of orbits that first appeared with sodium.

It was these facts that led to the concept of electron shells. The radius of a shell denotes the average distance of the electrons from the nucleus when the atom is in its normal state and unexcited. When an electron shell is full, as in the case of helium, neon, argon, or the other inert gases, the atom is inert and is un-

able to take part in any chemical combination. This property of helium has made it useful in balloons, since its chemical inactivity makes burning or exploding an impossibility.

In the order of increasing radius, the electron shells of a heavy atom contain two, eight, eight, eighteen, eighteen, and thirty-two electrons. When an outer electron shell becomes filled the element is inert. When it contains only a single electron the atom has a valence of one and metallic properties. When it lacks one of being filled the element has a valence of one and nonmetallic properties. Sodium with one electron in the outer shell can thus combine with chlorine, which has only seven electrons in the outer shell and thus lacks one as compared to the full shell of eight. The arrangement of atoms with respect to the condition of their outer electron shells is apparent in the second or newer form of the periodic table.

Although perhaps not immediately useful to the chemists, the Bohr atom model led to the adoption of the Lewis-Langmuir model of the chemical atom, a model which has proved important in the study of the way in which atoms combine to form molecules.

In this chemical atom model, first proposed and used by Lewis but later also by Langmuir who extended the theory, interest is centered not on the orbital motion of the electrons nor in fine distinctions concerning their distribution around the nucleus. The model is almost a static model, with electrons distributed around the nucleus in some symmetrical manner, in shells. Shells of increasing radius were assumed to

be stable if they contained 2, 8, 8, 18, 18, or 32 electrons, in accord with the facts of the Bohr theory. It is true that electrons at rest cannot be made to assume any stable configuration about a positively-charged central nucleus. The orbital motion is not denied, it is only neglected for the time being.

The Lewis-Langmuir theory of atomic structure explains the combination of two atoms to form a molecule in the very simple manner mentioned briefly above under the discussion of valence: an atom containing only one electron in its outer shell can combine with an atom whose outer electron shell lacks only one electron of being full. Let us continue to use the illustration of sodium and chlorine. In that case the outer or valence electron of the sodium atom is able, after combination with the chlorine atom, to circulate about the nuclei of both atoms, and this electron is shared by both. In the case of the combination of two hydrogen atoms to form the stable hydrogen molecule, two electrons move around a pair of nuclei. This case is so important that Lewis was led to the conception of an electron pair, shared by two atoms, as representing the typical chemical bond. There are exceptions to these rules, as there are to most rules, even in science.

The theory of chemical combination outlined above has proved very useful, especially in studying the combination of atoms and molecules to form crystals, and has in many cases enabled the understanding of why the shapes of crystals are so definite. Like most scientific theories it has been open to argument and disagreement, especially since the Bohr theory has been

to a degree superseded by the newer theories of quantum mechanics.

But even before the advent of quantum mechanics, notable advances were being made by Langmuir in his study of surface films, a study which has given much information about the nature of the chemical bond and of catalytic reactions, as well as gaining for Langmuir himself the Nobel prize in chemistry.

It may be of interest to note that Langmuir, the inventor of the mercury condensation pump, without which the attainment of the high vacua necessary for modern x-ray and radio tubes and for much of present-day research apparatus would be difficult, was drawn to the study of surface films by an early examination of the behavior of incandescent lamps, especially their filaments. The efficiency and length of life of such a filament depends to some extent on the condition of the filament or the filament surface. In the vacuum tube of radio, where a large yield of electrons from the hot filament is desired, the surface condition becomes of the greatest importance.

Gas molecules, under ordinary conditions, tend to collect on a liquid or solid surface in a unimolecular layer, that is, in a layer which is only one molecule thick. Saturated vapor can of course collect in much thicker layers. Water condensed on the surface of a cold drinking glass is plainly visible, whereas a unimolecular layer of water on glass would be invisible. It is difficult to measure directly the thickness of such thin films, films which may be as thin as a hundred-millionth of a centimeter, but there are indirect ways

of obtaining the information. For example, a drop of oil placed on water will spread out. By noting the area covered by the drop and knowing the density of the oil and the mass of the drop it becomes a simple matter to compute the thickness of the film. In general the oil spreads out until the surface film is about one molecule thick, after which it spreads no more.

Langmuir's idea was that surface films, especially films of gas on metal surfaces, were held by chemical forces, forces which may be very strong over short distances, but which become insignificant over distances which are somewhat larger than the diameter of a molecule. The Lewis-Langmuir atom provides such forces, which are effective over a distance equal to the radius of the outer electronic orbits, for the force depends essentially on the outer, or valence, electrons. Beyond these orbits the force acting on another particle is made up of the sum of forces from the electrons and the nucleus together, which tend to balance out.

Here was an idea that might have important things to say about catalytic reactions, for it has been known that it is the surface of a catalytic agent that is effective. It occurred to Langmuir that the condition and arrangement of the surface atoms of the metal, as well as the atoms or molecules of adsorbed gas, that is, the gas molecules which have attached themselves to the metal surface, might have much to do with the effectiveness of the surface as a catalyst. He has since shown that his surmise was correct, thereby giving to chemical research a new tool, as well as widening the field of operations for the practical chemist.

Let us take a typical case. Carbon monoxide, that poisonous gas present in coal gas, illuminating gas, and the exhaust from internal combustion engines, will ordinarily continue to exist unchanged in the presence of atmospheric oxygen. But in the presence of a charcoal surface and oxygen it will be oxidized by the atmospheric oxygen into the harmless gas carbon dioxide, the gas used to give the pep to carbonated beverages. Clearly this action is catalytic, and Langmuir undertook to find out why.

Langmuir envisaged the interplay of the molecules present, and came to the following conclusions:

Molecules of carbon monoxide are driven up to the charcoal surface by their gas-kinetic energies and become adsorbed. In so doing there appears to be a preferential direction for adsorption so that the molecules of carbon monoxide are all attached to the charcoal surface in the same way, leaving similar parts of the molecules pointing out into space. It so happens that the exposed parts of these molecules are more vulnerable than is the molecule as a whole to the oxygen of the air, and chemical reaction takes place, resulting in the production of molecules of carbon dioxide. Since the dioxide molecules are held less firmly by the charcoal surface than were the monoxide molecules, the dioxide molecules evaporate, leaving room for the adsorption of more monoxide molecules and their resulting combination with oxygen into dioxide molecules. The speed of the reaction depends on the amount of the charcoal surface which is covered with monoxide molecules, which in turn depends on the statistical difference between the speed with which

monoxide molecules approach the surface and the speed of evaporation of dioxide molecules. The theory has been checked by means of experiments on evaporation from hot filaments, and appears to contain a great deal of truth.

Langmuir has thus shown the relation between the adsorptive power of a catalytic surface and its catalytic activity, as well as facts concerning the orientation of adsorbed molecules, facts which become increasingly important in the field of organic chemistry where molecules are heavy and complex and where molecular orientation becomes increasingly important in problems of reaction speed. These facts may eventually assist in the synthesis of some of the organic compounds so much needed in medicine. They are invaluable in the search for a more intimate relation between chemistry and the life processes of cells, plants, animals, and man.

In the meantime another relation was being found between chemistry and the quantum theory, a relation not directly involving the Bohr atom model.

It will surprise many to learn that Einstein has made important contributions to chemistry. His name has already entered this narrative several times in connection with relativity, the expanding universe, the quantum theory, and the theory of the photoelectric effect. His name now enters again under the subject of chemistry, for it was he who first showed how the quantum theory could be connected with the theory of chemical reactions.

In a chemical reaction energy plays a most impor-

tant part. In some reactions energy is required to enable the reaction to take place, while in others, such as the union of illuminating gas and oxygen, energy is liberated. It is true in most cases that some energy must be put in to start the reaction. The question has always been present as to where the energy came from that entered into chemical reactions. Although it had been suspected that incident radiation might in some cases provide the explanation, a quantitative theory was still needed, a theory which would give numerical predictions that could be checked by carefully controlled experiments. Such a theory was given by Einstein.

According to the quantum theory, radiation is emitted or absorbed only in finite units of size $h\nu$, h being Planck's constant, and ν the frequency of the radiation absorbed or emitted. This fact, so well established in the quantum theory of spectroscopy and of the photoelectric effect, was now turned to account to explain chemical observations.

Einstein assumed that radiant energy falling upon the reagents, in the sort of reaction which was aided by light and which did not take place in the absence of such radiation, was absorbed only in quantum units, an integral number of the units $h\nu$. This energy was then internally converted in some manner and the energy made available for the chemical reaction. This theory of photochemistry is somewhat complex, and has been made even more so by recent extensions with the help of statistical mechanics. Its predictions do, however, agree in detail with chemical observations.

Since the entrance of the quantum theory into the theory of photochemistry, great strides have been made, principally by Taylor and his associates, especially Eyring, who has received high honors for his work. The new results explain many perplexing facts about surface chemistry and catalysis on the basis of the new quantum mechanics.

Let us recall, as an introduction to the latest work of Eyring, a few features of quantum mechanics.

The equations of quantum mechanics, describing the behavior of a particle or particles, have the form of well-known equations describing a system of waves. They have been interpreted to represent a system of probabilities, so that the wave equation for an electron represents the probability that the electron will be at a given place at a given time. A moving electron either inside or outside an atom is represented by a distribution function showing the probability of the electron's existence at this or that point, giving what amounts to the charge density in the space available to the electron. These facts have been discussed more fully in a previous chapter. They are only recalled here to clarify the line of thought followed in their adaptation to chemistry.

In quantum mechanics, an important concept is that of electrical potential, which is allied to potential energy. The potential at a point is equal to the potential energy of unit charge placed at that point, or the work needed to bring the unit charge to this point from infinity.

What happens when an electron decides to break

away from an atomic nucleus, as it often does when the nucleus is radioactive?

The electron must overcome a field of electrical force in order to escape, that is, work must be done on the electron to get it out of the nucleus. According to older theories, the electron would escape if it possessed enough initial energy to escape from the electric field of the nucleus and pass through the nuclear potential barrier. All electrons possessing this initial energy would escape, and none having a smaller energy could possibly do so.

Quantum mechanics has changed all this. It is now recognized that some electrons can escape which have a smaller energy than that required to pass the potential barrier according to the older theory. Here's how:

The electron in the nucleus is no longer considered to be a point charge. Its position is indefinite, the charge being spread out over a region each part of which contains a probability for the existence of the electron. The region can be represented as a wave packet of finite size, caused by the interference of wave trains in the manner previously described. It may so happen that one end of this wave packet, or region in which the density of charge is not zero, may traverse the potential barrier, and sometimes the probabilities may be so distributed that the entire wave packet will follow through. Thus the electron escapes from the nucleus, even though in some cases the electron when considered on older theories does not have sufficient energy to do so. Whether an electron will escape depends on the distribution of probabilities,

which are calculated by the equations of quantum mechanics.

These are the concepts which Eyring has adopted in formulating his theories of chemical combination. Instead of considering potential barriers around a nucleus he uses the barriers which represent the binding energies holding atoms together in the molecule. The amount of energy at a given distance from an atomic center can be plotted to form a curve, or rather a curved surface, looking somewhat like a system of mountain ranges separated by valleys. The valleys represent stable conditions of the molecules. If chemical reaction is to take place enough energy must be given to the molecule to overcome atomic attraction, or in other words to carry the system over the top of a mountain range representing the potential barrier. If this happens, and the probability of its happening is given by quantum-mechanical equations, the molecule will have been broken up, and the atoms are free to unite with other atoms to form new molecules. The chemical reaction then proceeds.

Although the theory is not as yet complete, its usefulness has been amply shown. It enables the computation of reaction speeds, which can be measured. In particular it points to a very low speed of combination of hydrogen and fluorine under ordinary conditions, which was supposed to be in disagreement with experiment, but which is in complete accord with newer and more accurate tests. It can also tell which of several modes of reaction is the actual one, since for

this one preferred mode the calculated speed of reaction will be greater than for all the others.

Thus one more step has been taken along the road leading, let it be hoped, to a complete understanding of the nature of chemical processes and of the chemical bond.

While this theoretical work goes forward, other workers are busily searching for clues in a field which, although in reality pure science, does have more immediate and practical ends in view: the field of chemistry in the service of medicine. The organic chemist is looking for ways to synthesize new anesthetics, to purify and synthesize the hormones, vitamins, and if possible the enzymes, all of which are so important for the processes of life. Some of these researches will be described in a future chapter on biochemistry, when it will be shown how advances made on this front may lead scientists a little farther toward a complete understanding of what makes a living thing.

The Frontiers of Health

CHAPTER XV

THE SCIENCE OF HEALTH

In many parts of this country, especially in the cities, the family attic has become a thing of the past. A recent exploration in one such attic, among bundles and packages yellowed with age, led to an unusual experience. The contents of the package was in no way unusual, for the enclosed picture was a familiar one, in a rather ordinary frame. The interest lay entirely in the fragile sheet of newsprint in which the picture was wrapped. Across the top of the page, in large letters, appeared the words: "Thousands More Die of Yellow Fever."

In these days of organized public health agencies, of vaccination, and of preventive medicine in general, it may come as a surprise to many to read of the disastrous epidemics that ravaged sections of the country a few generations ago. Yellow fever was not the only offender. Smallpox, diphtheria, typhoid, malaria, one or all of these were liable to pop up at any time or place, to kill more thousands or ten thousands. Those who had managed to remain in sound health were often forced to choose between severing their household ties and departing to other sections of the country, taking with them such of their belongings as could be piled on the rear of the family buckboard, or remaining to face almost certain death. Groups

of citizens were organized as sentries, to prevent the entrance of persons from infected areas into their as yet immune township. The sentries were instructed to turn back all persons from towns which the epidemic had reached, and were prepared, in carrying out their instructions, to shoot to kill.

Today one sees a very different picture. About all that the average American of the present knows about quarantines is that his home may be isolated for a few days when he has a case of measles, or that he may be prevented from carrying certain green vegetables across state lines. Occasionally, as during the influenza epidemic of the war years, schools may be closed for a few weeks, and persons in public places may be required to wear masks. The frontiers of health have ceased to be defended by firing squads. The public health officer has taken their place. Vaccines, antitoxins, scientific protection of food and water supplies, and education in public health, all based on scientific researches, have helped to bring about the new era of health in which we live.

In organized towns and cities, epidemics of waterborne typhoid fever have become a thing of the past. Sources of water for drinking and domestic use are now chosen whenever possible from bodies of water uncontaminated by sewage, and strict control is maintained to prevent the entrance of impure substances. As an added precaution, water stored in reservoirs is filtered at least once, and sometimes more often. Small quantities of chlorine are generally added before the water is distributed to remove any remaining traces

of pollution. Frequent analyses, both chemical and biological, are made, and treatment of the water adapted to suit changing conditions.

Many cities, such as those surrounding the great lakes, are forced to use water into which sewage has been emptied. Such water can be made fit for drinking by suitable treatment. But it is possible to include as well treatment of the sewage material, rendering the most extreme measures for purifying the lake water unnecessary. A few cities have already installed sewage purification plants, taking most of the impure material from the efflux and returning water to the lake which although not entirely pure, contains only such impurities as can be removed by the natural process of oxidation, or by simple filtration and chlorination. The product of such purification plants yields a cheap and effective fertilizer, putting to use the material that would otherwise become a public nuisance, often collecting on the surface in a scum that is both unsightly and odorous.

Control of water supply does not stop with purification. In some places where a deficiency in iodine results in a spread of goiter or other thyroid disorders, iodine salts may be added to the water. However the water is treated, it is always under the strict control of the analytical chemist and the biologist. Sanitary engineering is becoming one of the recognized branches of the science of public health.

At one time it was dangerous to drink milk. Many severe outbreaks of typhoid and tuberculosis, especially among children, have been traced to infec-

tion in supplies of this most necessary food, whether from infected cattle or from lack of cleanliness in handling. Milk is an excellent medium for the growth of bacteria. Now that most cities require pasteurization of all milk sold (even in country districts pasteurized milk is usually obtainable), there is generally no danger in drinking milk fresh from the bottle. Add to this the rigid government inspection of herds of cattle on milk farms, and it is easy to see why typhoid is no longer a constant threat. If pasteurized milk is for any reason not obtainable the process can easily be carried out at home, as indeed is generally done when infants are fed, in order to kill any bacteria that may have entered since the milk was prepared or the bottle opened. Meat is subjected to nearly as close scrutiny as milk, and government inspection stations are widely distributed.

An exciting chapter in the story of public health is concerned with the insect-borne diseases. The very building of the Panama canal testifies to the successful control of the most deadly of these, yellow fever and malaria.

Pioneer work in American medicine had already shown that Texas fever was carried from one animal to another by insects, and malaria was known to be transmitted by mosquitoes. After the ravages of yellow fever in this country, and in the canal zone when the French were making their unsuccessful attempts to dig the canal, being continually thwarted by the same enemy, it was suspected that mosquitoes were the carriers of the organism responsible for this fever.

The story of the heroic experiments of Reed, Lazear, and their colleagues in Cuba has been told so often that it has become almost a folk-tale. It is a story that can bear retelling, for it is typical of the enterprise and selfless interest among members of the medical profession, justifying the confidence that has been placed in its members. Once the truth had been found out it became a comparatively simple matter to drive out the mosquito by preventing its breeding. Swamps were drained, pools were covered with oil, and the jungle became healthy. Today as the result of the sanitary engineering of Gorgas the canal zone is a more healthful place than some other regions supposed to be ideal for human habitation.

Recent work at the Rockefeller Institute and the Pasteur Institute have made possible an inoculation against yellow fever that is effective for at least two years.

It is only necessary to recall the control of malaria, partly by eliminating the mosquito, partly by dosing with quinine, and the control of hookworm by enforced sanitary measures. Today interest centers in epidemic encephalitis or sleeping sickness, and poliomyelitis or infantile paralysis. Much investigation is being done looking to the control of influenza, which struck an unexpected and deadly blow during the closing years of the war. And not to be forgotten is the common cold.

The American farmer has benefited from insect quarantines. No longer is the Florida fruit grower harassed by the ravages of the fruit fly. State lines,

especially when reinforced by natural barriers, have been made effective in preventing the spread of these natural enemies, and the quarantine of vessels from foreign ports which are found to carry undesirable insects has aided in decreasing the economic losses resulting from their entrance.

The work of the public health department of the central government is augmented by state and city health units, including research laboratories, clinics, and means for educating the public in the ways of healthful living. While one branch is discovering new means for preventing the spread of encephalitis, another branch is already putting into practice the discoveries of a few years ago. Diphtheria has become an unnecessary disease because of work done in public health laboratories under the direction of such men as Park. Even the poor can bring their children for inoculation to any one of many stations maintained by health departments. Thus the dreaded diphtheria is yielding to control just as smallpox has already yielded. The larger public health laboratories also have facilities for testing and controlling the purity of drugs and vaccines, and for discovering new and better means for their preparation.

Many laboratories are carrying on experiments concerning the cause and cure of cancer. From occasional publications it is evident that progress is being made.

We are told by medical associations and public health agencies that cancer can be cured if treatment is begun early enough, as soon as the characteristic

symptoms appear. In such cases the growths can be removed by surgery, or by the use of radium radiations or x-rays. Each year more powerful x-ray tubes are being supplied, and today tubes are available which outdo radium itself in producing radiation of great intensity and penetrating power.

Too little is known about cancer. It is known that the growths are able to spread and produce tumors in other parts of the body, and that chronic irritations may induce the growth of a tumor which may become malignant. This knowledge can be and is used in diagnosis, treatment, and when the cooperation of the patient makes it possible, prevention.

Researches are concerned with the initial causes of cancerous growths, with the difference between benign and malignant tumors, and with the methods by which the tumors spread. The search is being made for some substance which, injected into the blood stream, will kill the tumor cells without injury to other parts of the body. Now and then some encouraging report will appear. Investigators in the laboratories of the U. S. Public Health Service have succeeded in transmitting cancer to guinea-pigs by inoculating the animals with microorganisms isolated from a tumor in a human body. Whether or not these men have isolated the "germ" of cancer remains to be seen. Other workers in the Public Health Service have studied the production of lactic acid in cancerous growths, and have attempted to tie up the newly discovered facts with known principles of acid control and carbohydrate equilibrium. Scientists at the Rockefeller In-

stitute have shown that extracts from tumors obtained from chickens exhibit the power of retarding or in some cases preventing the growth of new tumors, and that certain extracts from normal tissues of mice have the same properties.

It is not to be doubted that researches such as these will in the not too distant future place in the hands of the clinical technician a simple and infallible means for combating and controlling this dread disease of later life. So far this is little more than a hope, but a hope that is so strongly held that quantities of time and money are being spent in its pursuit, and pleas for more of both money and the time of trained research workers are often heard. For cancer will only yield to a concerted effort.

Today the elementary schools include much work for promoting the general health of the public. Children are taught the simple laws of health. They are taught to avoid accidents and are shown the elementary facts of personal hygiene. Studies made among school children have been important in the discovery of the factors of transmission and control of disease among groups. New knowledge of the science of nutrition has been applied to the school lunch rooms, resulting in an increased efficiency of the pupils, as well as the elimination of malnutrition with its attendant evils, tuberculosis and other illnesses that grow readily among undernourished children.

Much attention is being given to the provision of medical care for the public at reasonable cost. The report of a committee organized to study this prob-

lem has recently invoked much discussion. It discovered that under a socialized scheme of medical organization the public could obtain much better care than it does at present, with but little greater financial outlay. The suggested plan has met with criticism. Some fear that the intimate relation between the family doctor and his patients would be lost, others fear that the patient would be assigned to inferior doctors. These are details that will have to be worked out. It is a fact that successful doctors are very often crowded for time, while many young and thoroughly capable doctors have much idle time on their hands. Both situations are wasteful of the doctors' time and of the patients' time and money. It is suggested that the organization in a given community should center around a hospital with its complete staff and equipment. The patient could thus choose between several doctors, and would have the services of the clinic, the hospital laboratory, and the visiting-nurse service, always at his call. The yearly subscription for these services, if organized on some such basis, would on the average be no more than the average cost per year of medical care under the present individualistic arrangement, and if properly managed in accord with the established ethics of the medical profession could result only in improving the health and the standard of medical care of the community. In fact a certain amount of socialized medicine already exists in the tax-supported public health institutions.

With this rapid survey of the field of public health we pass at once to a closer examination of some of the

investigations now occupying the staffs of laboratories where medical problems are under scrutiny, many of which will before the end of another decade have moved out into the practical field of the clinic and the practicing physician. Some have already done so to a large extent, others are not quite ready for the public.

Let us see what work is now being done on the frontiers of health.

CHAPTER XVI

IMMUNOLOGY

When Jenner, in 1798, had inoculated a child with the germs of cowpox, and when later he had proved that a number of children so inoculated were immune to infection by the dreaded smallpox, the science of immunology was born.

Jenner's discovery came as the result of an observation that anyone could have made, and that many probably had made: farm workers who had contracted cowpox appeared to be immune to smallpox. But only after Jenner had put this observation to the test, had deliberately inoculated living persons with cowpox, and had demonstrated that such persons were unable to contract smallpox, could the idea be accepted by the medical profession and the public. Today, as is well known, the vaccination of children for smallpox is compulsory in many parts of the world.

Vaccination for smallpox thus became established several decades before the germ theory of disease gained a foothold as a result of the work of Pasteur and Koch. Bolstered up by increasing knowledge of the bacilli and protozoa which in most cases are the cause of illness, the science of immunology has grown apace. Diphtheria has ceased to be a scourge of childhood, meningitis has been brought under a de-

gree of control, and it is hoped that in the near future other epidemic diseases will also yield.

What are the facts which underlie the science and the practice of immunology?

Diphtheria is caused by growth in the body of a characteristic bacillus. The growth of diphtheria bacilli is accompanied by the production of a chemical substance, diphtheria toxin, which in itself is sufficient to produce all the symptoms of the disease. Inoculation with sufficient quantities of this toxin will produce a severe case of diphtheria. It so happens, however, that the presence in the blood stream of this toxin causes a reaction, whereby a substance is produced which is able to counteract the poisonous effects of the toxin. This substance is called antitoxin.

The earliest mode of treatment for diphtheria was analogous to vaccination for smallpox. Blood serum from horses or other experimental animals which had recovered from a case of diphtheria and were therefore immune was injected into human beings, resulting in a certain degree of immunity for the person so treated. This immunity was not permanent, and for a most interesting reason: horse serum is not identical with the serum of human blood. The dissimilarity of blood from different species, or different groups of the same species, will be discussed in a future chapter. The result, in the present case, was that the action of human blood on the injected serum rendered the acquired immunity short lived.

Two alternatives presented themselves: Antitoxin prepared from human beings who had from previous

attacks become immune was effective but could not be prepared in sufficient quantity. Injection of the toxin into human blood might produce immunity but was attended with grave dangers.

The final solution, worked out in detail and put into clinical practice on a large scale by Park in the public health laboratories and clinics of New York City, was essentially a compromise. Modern practice depends on the injection of a mixture of the toxin with antitoxin prepared with the use of experimental animals. The antitoxin renders the patient immune for a time, long enough to enable the blood of the patient to prepare its own antitoxin under the stimulus of the injected toxin. When the immunity from the original antitoxin has worn off a new and permanent immunity has been built up.

The action of diphtheria toxin has become the basis of a test for immunity, called the Schick test. Inoculation of the skin with a small amount of the toxin unmixed with antitoxin will have no effect if the subject is immune. If he is not, a reddening and slight soreness of the inoculated skin will result.

Widespread use of the toxin-antitoxin treatment has made great inroads on the ravages of diphtheria, until it has truthfully been said that no child need have this disease. With the treatment of every child, the disease could be wiped out completely. Now that immunity to yellow fever can be obtained by inoculation, the inroads made by this disease will also be further reduced.

For other epidemic diseases no satisfactory mode

of supplying immunity has as yet been found, although intensive studies are being carried out in public health laboratories, at the Rockefeller Institute in this country, and in university and private laboratories. Variations of the toxin or the antitoxin treatments, or of both together, are being tested. Cultures of killed bacteria may be the material used for injection, or weakened or attenuated strains of living bacteria, or of the resulting virus. At the same time work is being done in an attempt to find and identify new bacteria, and to discover the nature of the virus which is produced by each. Much of this later work really comes under the head of biochemistry or biophysics, and will be discussed presently. First will be described some recent work on possible ways of providing immunity to such diseases as meningitis, poliomyelitis, and encephalitis, as well as the ever threatening influenza.

As in the case of Jenner's discovery, it may not be entirely necessary to recognize the bacteria in order to prevent their growth. In some instances, however, such knowledge is essential, and it is true of this as of every other branch of science that no real knowledge, once attained, is ever wasted.

Cerebrospinal meningitis is a devastating disease which can occur, and has occurred, in severe epidemic form. The bacillus responsible has been isolated, and the mode of entrance determined. The bacilli enter through the nose, and move to the brain and the spine, where they multiply and produce all the distressing symptoms of this disease. In a milder form, which is

not epidemic, the illness can be produced by the bacilli of tuberculosis, pneumonia, and influenza, a fact which may explain the prevalence of meningitis cases following a severe influenza epidemic. A more or less satisfactory mode of treatment has been developed by Flexner of the Rockefeller Institute, who has found that spinal injection of the characteristic antimeningococcus, as it is called, will reduce the severity of the disease in a considerable number of cases. But the period of research is by no means past and the work goes on, animals being inoculated with the bacteria and with various sorts of serum in attempts to discover some certain and practical means for bringing meningitis under control.

The courage which President Roosevelt has shown in overcoming the results of his attack, and his formation of the Warm Springs Foundation for the treatment and rehabilitation of other sufferers, is a constant reminder of the necessity for finding a means for rendering poliomyelitis, or infantile paralysis, one of the diseases which will be dreaded no longer. It can hardly be so classed at present.

No characteristic germ of poliomyelitis has so far been found. The causative agent has accordingly been classed as a filterable virus, which will pass a porcelain filter. Bacilli or protozoa, on the other hand, are retained by the filter and can then be studied under the microscope, as indeed they could in the unfiltered solution. A discussion of experimental work on the nature of the filterable virus will have to be left for a future chapter. The virus can be studied by its

effects, for it is able to produce the characteristic disease on inoculation.

The mode of entrance of the infection is known. Like the germs of meningitis and of influenza, the agent responsible for poliomyelitis enters through the nose or throat. Suspicions that it is carried by insects, based on the fact that the disease is prevalent in epidemic form only during the warm months when insects are present in large numbers, have not been confirmed.

For the study of this disease monkeys have proved to be ideal experimental animals. If the symptoms resulting from an injection of virus had not already set in, treatment with serum from animals known to be immune because of having recovered from an attack of the disease was found to be effective. In such animals the symptoms failed to appear.

It is known that many persons have suffered mild attacks without the paralysis characteristic of severe cases, often without realizing that they have been infected. Partly for this reason, the majority of adults are immune to the disease. Much of the experimental investigation, in which Flexner has been active, has been based on the above facts.

It has been found that injection of children with serum prepared from the blood of normal adults, whether or not they are known to have recovered from an attack of poliomyelitis, is effective in giving immunity to the child. Such has been the basis of experiments carried out in recent epidemics. In general, whether the subject was a monkey inoculated with

monkey serum, or a child treated with human serum, it appeared that injection of the serum, before exposure to the disease or in the case of experimental animals before inoculation with the virus, was quite effective in preventing infection. The disease might be controlled if injection of the serum took place before the disease had time to develop. After the characteristic symptoms appeared, the serum was worthless.

No certain means have been found by which infection with the virus of poliomyelitis can be ascertained until symptoms appear. The present mode of treatment offers immunity if performed in time, but is limited by the small amounts of immune serum obtainable. It is to be hoped that the intensive work now being done will lead before too long a time to a more certain method of controlling the disease, even after symptoms have appeared. Then poliomyelitis will take its place along with smallpox, diphtheria, and yellow fever as diseases which science has rendered preventable and unnecessary.

Since the recent outbreak of epidemic encephalitis, or as it is sometimes called, sleeping sickness, in St. Louis, this disease has been added to the others for which a means of control is being intensively sought.

Encephalitis is not identical with African sleeping sickness, a disease caused by the growth of parasitic protozoa in the blood. The latter disease is transmitted by the bite of the tsetse fly. Epidemic encephalitis, on the other hand, has not been found to be caused by protozoa, or even bacteria, and it is not

certain how it is transmitted from one person to another. It is known however that infection can enter through the nasal passages, as is the case with meningitis, poliomyelitis, and influenza.

A similar disease attacks horses, and in this case it has been ascertained that the virus is transmitted by mosquitoes. This fact, together with the prevalence of encephalitis in the late summer and fall, and in regions where mosquitoes breed, seemed to indicate that the virus might be transmitted from one human being to another in the same way. Tests made in the epidemic region, under the direction of Leake, have so far proved negative. The doctors working on the problem, and later a number of volunteers, failed to contract the disease after having been bitten by mosquitoes that had bitten infected persons. Possibly the results of these tests are not as yet conclusive. It appears that encephalitis, like poliomyelitis, may occur in mild form, often so mild that it is not recognized. Immunity may be conferred by such mild attacks, in which case the bites of infected mosquitoes would of course have no effect.

Although the agent responsible for encephalitis has not been isolated and recognized (it is probably a filterable virus), it has been found that monkeys will contract the disease, and that inoculation of a healthy monkey with serum from an infected one will produce all the characteristic symptoms. The strain of virus can thus be kept alive and active for experimental purposes, which is useful in the absence of an exact knowledge of the nature of the virus itself.

PLATE XVII

Blood parasite, and a blood cell.

From time to time announcements have been made of new modes of treatment that would render persons immune to tuberculosis. These announcements have always received wide publicity, followed by disagreement among workers in the field, and have finally dropped out of sight. As yet no certain and infallible treatment exists. But it is encouraging, in view of the tremendous toll taken by the so-called white plague, to know that the work goes on. Some day such an announcement may receive later confirmation in the work of widely separated investigators and the cure will have been found.

Besides immunization with bacterial cultures or with antitoxins prepared from them another mode of treatment for certain diseases is being developed.

Many primitive tribes have known that cinchona bark is effective in the treatment of malaria, and quinine, the pure active principle, is widely used by civilized peoples. It has been found that quinine kills the malarial parasite which lives in the blood of the sufferer. The efficacy of the treatment depends on the fact that the chemical will kill the parasite without harming the host. The difficulty in extending this mode of treatment to other diseases lies in the difficulty of finding suitable substances which will kill the invaders without damage to the person under treatment.

A start has been made in this new field of chemotherapy with the preparation by Ehrlich after many trials, of salvarsan, or arsphenamine. This chemical can safely be injected into the blood stream of the

human body and has disastrous effects on the protozoan parasites which cause syphilis. It is also effective against certain other protozoa which invade the body. Not as yet so successful is the preparation called Bayer 205, which contains no arsenic or other poisonous substances, but which to a degree is useful in destroying protozoan parasites without harming the host. Its discovery resulted from the observation that certain dyes would stain protozoa without staining the tissues of the human body. Such differential action is the basis of all successful work in chemotherapy.

Attempts are being made to prepare a synthetic material that can be used in place of quinine, and new compounds based on the healing power of chaulmoogra oil for cases of leprosy are being sought.

As yet the methods of chemotherapy have not proved effective against bacteria. Favorable results in the case of a few diseases resulting from the invasion of protozoa urge the organic chemist to continue his efforts to design molecules of new and more effective chemical substances, adding or subtracting atoms as observations indicate that the changes made will render the substance more useful for the purpose at hand.

In the meantime a new interpretation of a phenomenon already familiar to many workers in the field of bacteriology has been found to contain startling implications.

The laboratory of the bacteriologist is generally decorated with row upon row of small test tubes, their mouths stuffed with cotton, containing clear or cloudy

liquids. The contents of the tubes are cultures of bacteria, growing in solutions of broth and other substances which have been found to support bacterial growth. The growth of the bacteria is shown by the clouding of the culture medium in the tubes.

Often it is more convenient, especially for purposes of demonstration, to use a more modern technique. It has been found that bacteria will grow and multiply in a thin coating of agar and food medium which has been spread upon a glass plate. The absence of spillable liquid and the compactness of the cultured plate make for easy handling and transportation. Just as in the case of the liquid cultures, growth of bacteria makes itself evident by a clouding of the culture medium.

For a long time it has been known that cultures in test tubes occasionally clear up, often for no known reason, and that clear spots will sometimes appear on agar plate cultures. Only recently has this occurrence led the bacteriologist to a new conception and a new field of study: from this sort of observation arose the idea of the bacteriophage.

Phage is a term that has for some time been used in biology. Witness the word phagocyte. Appended to the word bacterium, it signifies killing, or living at the expense of bacteria. The word bacteriophage has been used, first by d'Herelle and later by others, to denote the agent responsible for the clearing up of parts of a bacterial culture, and for the production of the clear spots on agar plates on which bacteria are growing.

Anyone who has read the novel Arrowsmith will realize what a find this new field is for the bacteriologist. It has not as yet, however, reached anything like the stage of completion indicated in the novel.

What are the facts about bacteriophage, facts of observation that can be repeated and confirmed by anyone?

Cultures of bacteria obtained from sewage or from water into which sewage enters will often be found, when grown upon agar plates, to show the characteristic clear spaces, spaces in which bacterial growth is inhibited. Sometimes these clear spaces are small and few in number, sometimes they become so extensive as to cover the entire plate. Further, a sample of material taken with a sterile needle from the center of one of these clear spots and deposited on another culture plate is often able to clear a spot on the second culture.

It is easy to prepare very powerful samples of bacteriophage by filtering a bacterial solution containing it, then mixing the filtrate with a young bacterial culture. When this is done the bacteria appear to grow for a time, then disappear, leaving a liquid which has strong bactericidal properties. A drop of this liquid, even after tremendous dilution, will when spread over an agar plate containing a young bacterial culture produce the clear spots characteristic of bacteriophage. When a more powerful concentration of bacteriophage is spread over the plate, the bacteria disappear, and the plate becomes so clear that no trace

of anything resembling bacteria can be found, even under a powerful microscope.

What is the nature of bacteriophage? The substance will pass the finest of filters. It is able to increase in concentration and bactericidal power by the very process of destroying cultures of young bacteria. Accordingly some believe that it is a living material. One is led to recall the filterable virus, a substance which will pass through fine filters and which contains no cells or other bodies that can be seen under the microscope. That a filterable virus may be a living substance is shown by the deadly power of those substances responsible for the infection of animals and man with encephalitis and poliomyelitis, substances which can be grown in the bodies of infected animals to such an extent that an amount originally just sufficient to infect one animal can be made to produce enough virus to infect hordes. As will be shown later, the problem of the nature of the filterable virus may bring the biologist very close to the problem of life itself.

It is further supposed that bacteriophage exists in the form of ultramicroscopic nuclei or minute cells. If so they are far too small to be visible under the microscope. As is the case with any filterable virus, the only way to study the material is to observe its effects. A weak dilution of the substance will when spread over a young bacterial culture on an agar plate produce a few characteristic clear spots. If the mixture is twice as strong in bacteriophage the number of

clear spots will be doubled. Such observations can be repeated any number of times with the same result, and have led to the supposition that bacteriophage exists in the form of discrete particles. One particle is responsible for each clear spot on the agar plate. The size of the spot is an indication of the growth of the bacteriophage particle and the production of other particles. The size of the clear spot is limited by a sort of equilibrium between the growth of the bacteria and that of the bacteriophage. The latter is not very effective on old bacterial cultures. Additional experiments have shown that it can grow only in the process of destroying young bacteria. Once grown it is able to destroy older bacteria, but its own growth is inhibited.

Of what use is this new and interesting substance? Will it ever be of practical use in the clinic, or in preventing the spread of epidemics?

Bacteriophage appears to be most effective against the types of bacteria which grow in the digestive organs of men and other animals, especially in the intestines and colon. It may very well limit the severity of diseases such as cholera, and possibly plays an important part in cleaning up the infective agents in rivers such as the Ganges, in which its presence has been detected. Though most effective against young and rapidly growing bacteria, it does not appear to be effective in the presence of blood or pus, a fact which at the very start puts a limit to its possible utility. Apparently it will not, as was hoped for a time, prove useful in the treatment of blood poisoning.

Neither, it may be remarked, has chemistry as yet been able to provide a suitable material which can be injected into the blood and which will kill the invaders responsible for blood poisoning without damaging the owner of the blood system.

At present, bacteriophage is a substance of the greatest interest to the biologist intent on an understanding of the nature of life processes, and its study in the biological laboratory and in the field may lead to successes as yet only dreamed of, successes that may in time also become successes in preventive and curative medicine.

CHAPTER XVII

GLANDS AND VITAMINS

In former years the doctor was often able to do a great deal to cure disease, but in most cases very little to prevent it.

The progress of medical science has to a large degree enabled the medical practitioner to anticipate the onset of sickness. Vaccination has provided an effective means for preventing a threatening epidemic of smallpox, and the more recent toxin-antitoxin treatment for diphtheria has rendered another dread disease unnecessary. The scientific control and purification of drinking water and the pasteurization of milk have made typhoid a result of nothing but civic or personal carelessness. Medical attention is centering more and more on the prevention rather than the later curing of illness.

For centuries disease was considered to be evidence of the presence of some poison in the system, something that would have to be neutralized or eliminated in order to effect a cure. With the advent of the germ theory of disease, following the pioneer work of Pasteur and Koch, added weight was lent to this view, until it was believed that every malady could be traced to some sort of germ, bacterium, or parasite. Today, thanks to work that is no older than the present century, a new science of immunity has grown up, based

not on the control of germs, bacteria, parasites, or poisons, but on knowledge of the chemistry of the body. In this new age persons suffering from diabetes can by frequent injections of insulin retain full health and usefulness, while rickets, scurvy, and other diseases can be entirely prevented by the proper feeding of vitamins.

The idea of curing or preventing disease by supplying a substance in which the body is deficient rather than by eliminating a poisonous or harmful substance had its origin during the first few years of the present century, when the newer knowledge of glandular action began to accumulate. As a result a powerful impetus has been given to the practice of preventive medicine and public health.

A gland is a body organ which manufactures and secretes some particular substance needed in the physiological processes of life and growth. Glands have been recognized and studied for centuries, but the older knowledge included only such glands as secreted their products through definite channels or ducts, and into a particular part of the body. Glands in the mouth, for example, furnish saliva in a definite place and for a definite and well recognized purpose.

In the early days of medicine a certain type of glandular therapy was recognized. It was believed that certain glands, when added to the diet, would impart to the consumer the qualities of the animal from which the glands had been taken. Such qualities as heroism and bravery were in some cases sought in this way.

But with the advent of the present century came the discovery of the so-called ductless glands, the glands of internal secretion, or the endocrine glands, a discovery that opened an entirely new field for the research scientist and the medical practitioner. The field is still expanding and promising ever more hope for the curing of the ill, and the lengthening of human life.

The discovery of the mode of action of the endocrine glands came about in the following way:

It had been known that the pancreas secretes a fluid which is essential in the process of digestion. This fluid is deposited into the digestive tract just when it is needed, that is, when food has left the stomach and is passing on to the intestines. The question was, How does the pancreas know when to cooperate in the process of digestion? Does this organ receive a nerve message telling it that the digestive system is prepared for its secretion?

Nervous control of the pancreas would have agreed with accepted ideas of the control of body organs, but experiments soon showed that in this case the nerves had very little to say about what the pancreas did. For in an experimental animal this organ continued to secrete at just the right time and in just the right way even after all nerves connecting it with the rest of the body had been severed.

Accordingly the suspicion grew that the pancreas was subject only to chemical control. This suspicion was tested by injecting into the blood stream of the animal a preparation of membrane from the digestive

tract, the part in contact with the partly digested food when ready for the secretion of pancreatic juice. The pancreas, although isolated from the nervous system of the animal, immediately commenced to perform its duty. The control had thus been established to be of a chemical nature. The secretory power of the pancreas was set in action by some chemical produced in the digestive system when this particular secretion was needed.

The chemical agent responsible for the bearing of the message to the pancreas was given the general name *hormone*.

A hormone is thus a chemical substance secreted by a gland and deposited in such a way that it reaches the blood stream and travels to other parts of the body, where it produces its characteristic effects.

The mode of secretion of hormones, products of the glands of internal secretion, explains the late discovery of the hormones and of the action of the endocrine glands. The absence of ducts for glandular secretion left no obvious means of identifying the glands or the hormones. Besides, the secretions of the endocrine glands, in contrast to the secretions of many of the glands of external secretion which are provided with ducts, occur in very small quantity, so small in fact that in many cases the hormone cannot as yet be isolated and identified. Its presence in a solution must be determined by the biological action of the solution as a whole, as by watching the behavior of laboratory animals in which the fluid has been injected, or their behavior when the corresponding

gland has been removed. Moreover, many of the hormones are unstable, and are easily destroyed by the very chemical processes by which it had been hoped to purify and isolate them.

It should be mentioned that some glands, such as the sex glands, as well as the pancreas, all of which are provided with ducts, secrete separate substances and act both as glands of direct or external secretion and as glands of internal secretion.

So far, only a few of the several hormones which are known to exist have been obtained in pure form, and of these fewer still have been produced synthetically. The remainder must be used in solutions which have been prepared from animal glands and tissues, and whose purity and strength can only be known by testing samples of each batch on experimental animals.

One of the first hormones to be recognized, and certainly the first to be obtained in a pure form, is adrenalin, or as the U. S. Pharmacopoeia has it, epinephrine. This substance, secreted by the adrenal glands in animals and men, has since been prepared in the organic chemical laboratory, and the synthetic product is on the market.

The adrenal glands are situated just above the kidneys. Each of the two glands consists of two parts, the cortex, and the medulla.

It was already known that the health of the adrenal glands was necessary for the health of their possessor, although little information was at first available as to the part played by these glands in the proper func-

tioning of the body. It appeared that different roles were played by the cortex and by the medulla. Animals from which the cortex had been removed invariably died soon after the operation. Removal of the medulla, on the other hand, did not have such disastrous effects, although it produced easily recognizable symptoms.

A beginning was made in understanding the function of the adrenals when it was found that a preparation of the medulla injected into the blood stream produced an immediate and very marked rise in blood pressure.

Medical attention was thus beginning to center on the adrenal glands when the idea of chemical messengers, or hormones, was being introduced. In the meantime Abel at Johns Hopkins had succeeded in preparing a more or less pure concentrate of a product from the adrenals, and soon the pure hormone, adrenalin or epinephrine, was isolated by his students. Many interesting experiments were now possible: animals from which the adrenals had been removed could be injected with varying amounts of the hormone and their behavior and physiological reactions noted.

It was not long before chemists had succeeded in determining the molecular constitution and structure of epinephrine, and soon the substance had been prepared synthetically, thus verifying the structure as previously determined and providing a synthetic substance of great purity having all the desirable properties of the glandular substance. This hormone is now supplied both from natural and synthetic sources.

When and if the synthetic product becomes cheaper than that obtained by treating the glands from beef animals, the synthetic product will monopolize the market.

Adrenalin is widely used in medical practice. Its stimulating action renders it of service in cases of temporary heart failure, and sometimes in cases of weakened heart action. Its power of contracting the blood vessels, which is in fact one of the reasons for the increase in blood pressure following its injection, is utilized during surgical operations when bleeding from tissue surfaces hinders the progress of the operation. As an inhalant it is of use to sufferers from hay fever and asthma, relieving congestion in the nasal passages. Finally it is of the greatest use to the experimental scientist, for with it one is able to study the reactions of other body glands to the secretions of the adrenal medulla, thus learning much about the interdependence of the various glands, the action of the secretions of one upon another, and their ability to cooperate in maintaining the normal physiological action which is health.

At present much experimental work is being done in an effort to understand the adrenal cortex and the hormone which it produces. It cannot as yet be said that this work has been brought to a successful conclusion, for contributions from different laboratories are not always in agreement. It appears that the hormone has been separated in a pure crystalline form, but chemists have not so far been able to determine its

molecular structure or to attempt synthesis with much success.

The cortex secretes a substance which determines secondary sex characteristics, perhaps through some control over the endocrine secretions of the sex glands. The cortex also has a place in the hormone control of the female sex cycle. Death soon follows the removal of the cortex from both adrenals, but animals from which these glands have been removed can be kept in a state of normal health for an indefinite time by frequent injections of the cortical hormone.

Various theories are put forward to explain the life-giving action of the cortical hormone. It is considered by some to maintain the proper volume and concentration of the blood. Others believe that this action is a secondary result of other factors more immediately dependent on the presence of the hormone, such as carbohydrate metabolism and control of the amount of glucose present in the blood. The problem is complicated and is related to other hormone problems. Insulin, for example, which reduces the amount of glucose in the blood, also produces a reduction of blood volume and increased blood concentration.

The present unsatisfactory condition cannot exist for long, in view of the number of scientists in laboratories and clinics who are concentrating on the problem. The cortical hormone is now on the market and is proving to be a useful tool, not only to the experimental biologist but also to the practicing physician.

This hormone is indispensable in the treatment of Addison's disease, a long-known illness caused by a deficiency in the secretion of the adrenal cortex. That this disease is no longer invariably fatal is a triumph for medical science.

Our discussion of the adrenal glands, and of each part, the medulla and the cortex, contains features that are common to all medical and biological problems in which the endocrine glands are concerned. The physiology of the body is upset whether the gland secretes too much or too little of its characteristic product. If the gland secretes too much, it must be removed in part or completely; if it secretes too little, physicians have learned how to supply the deficiency, either by feeding the appropriate extract or by injecting it into the muscles or blood stream of the patient. The first method is of course preferred whenever possible, but when the preparation is rendered ineffective by the digestive processes it must be introduced hypodermically. In rare cases it is possible to control the secretions of a gland by controlling the secretions of some other gland. For example it is known that a diseased adrenal cortex will often produce masculine traits in young girls, traits or characteristics which ordinarily depend on the internal secretions of the sex glands. Instead of treating the sex glands themselves an operation on the cortex will in some cases restore normality.

Even before the discovery of hormone action it was known that a diseased thyroid gland would produce characteristic disorders in the body. Such cases were

at first treated, in the case of thyroid deficiency, by feeding extracts of thyroid; in the case of excess, by removing part of the gland itself. In fact it was observed that complete removal of the thyroid would produce the same symptoms occasionally appearing in otherwise normal persons. This observation led to the treatment of such persons with thyroid extract.

After the idea of hormones had appeared, search was begun for a hormone secreted by the thyroid. Kendall succeeded in isolating a substance which he called thyroxin, a substance containing a large proportion of iodine. Thyroxin could be used in place of the older thyroid extract in the treatment of thyroid deficiency. This active product of the thyroid gland has since been obtained in pure form, and has been synthesized. Recent reports tell of another chemical substance which has the same physiological properties.

Problems in which glands are concerned are complicated by interrelation between the various glands and their products. The functioning of the thyroid is controlled to some extent by the pituitary gland, located at the base of the brain, as is the functioning of the adrenal cortex. The utilization of vitamins by the body in the process of metabolism is also in many cases controlled by the presence in suitable amounts of glandular hormones.

Only a few of the many hormones which operate in physiological processes have as yet been isolated, and many experiments are still performed with the use of impure substances containing more than one

hormone as well as other organic substances. Only after the hormones have been separated and obtained in pure form will it be possible to perform clean-cut experiments to determine just what the role of each hormone is, what symptoms result from its excess or deficiency, and what effect each hormone has on the operation of other glands in the body. One can only guess how far science will be able to go towards producing greater health and longer life when the hormones have all been identified and isolated, and their especial uses learned.

Hardly more than a start has been made in understanding the internal secretions of the sex glands, secretions which produce the secondary sex characteristics. One or two indications have appeared, such as the effect of a diseased adrenal cortex on the regulation probably through the sex glands of normal sex characteristics. A hormone present in the female glands has been found in plants. One present during pregnancy has been discovered which when injected in female rabbits will result in the usual signs of pregnancy in rabbits, hair-loosening and nest-building. So little has been discovered in proportion to the mass of desired information which has not as yet been obtained that the field of endocrinology holds great hopes for the biologist and the experimental physician, and new discoveries are frequently announced.

The discovery of insulin has been of the greatest service to human health. Insulin is secreted by the normal pancreas, and controls the metabolism of carbohydrates. If the pancreas is unable to secrete its

proper supply of insulin the body is not able properly to assimilate sugar and the symptoms of diabetes appear. Formerly the diabetic, by means of the strictest diet, might be able to maintain normal health, but more usually the symptoms became aggravated and the patient died. Today, with frequent injections of insulin, the diabetic is able to live a normal life in every way. Insulin is destroyed by the digestive juices and consequently cannot be administered by the mouth. If present researches attain success in finding a new form of this substance which will not be rendered inactive in the stomach, it will be far easier for the patient to take his daily dose, and many who are at present unable to make the daily injection will then find it possible to preserve their health.

Along with the chemical regulators of the body, the hormones from the endocrine glands, another class of chemical regulators has been studied, substances normally included in the diet of healthy persons, generally derived from plant substances, and called vitamins. Hormones, on the other hand, come principally from animal products, and are produced in the human body.

The addition of vitamins to the diet is not the same as the addition of iodine to the diet of persons suffering from thyroid disorders. Iodine supplies a deficiency, that is true. But iodine is not a chemical regulator, whereas vitamins are.

Like the hormones, vitamins are substances about which it may be said, A little goes a long way. Even in extreme cases, the daily dose of any of the vita-

mins, if obtainable in pure form, would be far smaller than the smallest amount of material that can be weighed on the analytical balance. The size of the dose of any particular vitamin preparation is determined in relation to the amount needed to produce or to suppress some characteristic symptom in an experimental animal.

Although direct knowledge of the vitamins, like the hormones, is no older than the present century, their discovery is based on much older knowledge. Such knowledge as the fact that scurvy develops in the absence of fresh fruit and vegetables in the diet, and disappears when these foods are included, is as old as most of the accepted facts of modern medicine.

The newer knowledge of vitamins arose as a result of feeding experiments performed under carefully controlled conditions upon domestic animals. In one series of experiments done at the University of Wisconsin, calves were arranged in groups, one of which was fed entirely on wheat products, another on corn products, and a third on oat products. In other experiments groups of animals were fed on diets which included certain foods such as milk or special proteins, and excluded others. By noting the behavior and conditions of health of each group of animals and by changing the experimental diets as new facts were discovered, the factors in the food which though in minute quantities were instrumental in maintaining the health of the animals were in a sense isolated. These factors were called vitamins.

A normal diet must include, besides the energy foods, a small amount of the vitamins requisite to health, otherwise the symptoms of malnutrition and of scurvy, rickets, pellagra, and the other deficiency diseases will appear.

Moderate success has attended the separation of the vitamins in pure form. Synthesis, which must be preceded by correct and complete analysis, has recently been achieved for the case of vitamin C. Sufficient knowledge has accumulated to enable the proper diagnosing of dietary deficiencies, and their control by the feeding of products containing the necessary vitamins.

Fat-soluble vitamin A is found in cod liver oil, butter, and many vegetables. It is obtainable as carotene, the coloring matter in butter, egg yolk, carrots, and other vegetables. It is believed to play an important part in building up resistance to the common cold. Its presence is necessary for growth.

Water-soluble vitamin B has since its discovery been shown to correspond to two substances which had been tentatively called vitamins F and G. These substances are now called vitamins B_1 and B_2. The first is antineuritic, while the second is a pellagra preventive.

Vitamin C is found in orange juice, and in fresh vegetables. It is the material which prevents the development of scurvy. Modern explorers include among their provisions sufficient dried fruits and lemon juice to enable a daily dose of vitamin C to be

given to every member of the expedition. The dread enemy of long ocean voyages of the past has thus yielded at last to the progress of science.

Vitamin D prevents rickets. It is present in cod liver oil and in grain products that have been radiated with ultraviolet light. This property of wheat products to produce the vitamin under the action of radiation has been utilized under patents obtained by Steenbock of Wisconsin in the preparation of viosterol, which results from the exposure of ergosterol, a wheat product, to ultraviolet radiation. If vitamin D is indicated, a few drops of oil containing viosterol, as sold at the corner drug store, included in the diet by adding to soup or other foods, eliminates the unpleasantness of taking cod liver oil. Other preparations on the market include pills containing both vitamins A and D, a more perfect substitute for cod liver oil. Hens that have been radiated with ultraviolet light lay eggs containing vitamin D. This vitamin is also found in milk from cows that have been exposed to the summer sun, or to ultraviolet light. Children who receive plenty of sunlight or ultraviolet do not contract rickets even when vitamin D is almost entirely absent from the diet. In this, as in many other instances, an overdose of either radiation or vitamin D is attended with danger.

Vitamin E is a comparative newcomer, but its properties have been studied to a considerable extent. Without its presence animals are unable to reproduce. It has accordingly been called the reproductive vitamin. It is present in pineapples.

The newer science of nutrition depends largely on a knowledge of the vitamins, and the science of endocrinology on a knowledge of the hormones. The two branches are related and it is known in some cases how the presence or absence of a particular vitamin in the diet will influence the production and utilization in the body economy of a particular hormone. Although much more remains to be discovered in both fields than is now known, the present knowledge has proved of the greatest use in the clinic, and in the field by the country doctor. Public health services, both in their experimental laboratories and in their departments devoted to public education in the ways of health, are rendering the new discoveries more serviceable to the public. The treatment of deficiency diseases, whether by hormones or vitamins, has become an established part of medical routine, and preventive medicine has become an exact science.

The Secret of Life

CHAPTER XVIII

BIOCHEMISTRY AND BIOPHYSICS

In nearly every branch of human activity the present is an age of specialization.

The physicist, chemist, biologist, or engineer each has his particular field of investigation. He begins to concentrate on studies in his chosen line during the early years of his college career. Engineering freshmen or sophomores are asked to choose between mechanical engineering, civil engineering, electrical engineering, or aero-engineering, and sometimes industrial engineering. Physicists, chemists, or biologists are given a few more years to make up their minds, and often wait until the years of post-graduate study or even later to choose their particular line of investigation. A physicist will then become a specialist in cosmic rays, or perhaps in the theory of atomic structure. An astronomer will concern himself with the statistical structure of galaxies, the spectroscopic examination of spiral nebulae, or the study of planets in the solar system. One biologist will decide on the investigation of protozoa or bacteria, while another will interest himself with the study of frogs, rabbits, or hens.

The modern trend toward specialization has become necessary since the great expansion in human knowledge has made it quite impossible for a single man to

acquire an intimate understanding of all branches of science. Experimental investigation must of necessity limit itself in order to be fruitful, and many scientific investigations now being performed are so complex that even the entire lifetime of one man is insufficient for their solution.

In past years a scientist was accustomed to call himself a natural philosopher, and was at home in any of the sciences. He was prepared to teach a course in biology, natural history, or electricity, and his hands were trained both in anatomical dissection and in the construction and use of electrical and optical apparatus.

Cooperation between workers in the various branches of science is desirable, and in some cases is being achieved. But perhaps the greatest hope of a level of achievement impossible under extreme specialization lies in work performed on the borderline where two sciences meet. Physics and astronomy have found a common ground in astrophysics, while physical chemistry, intent on searching out the secrets of atomic structure, leans sometimes toward chemistry and sometimes toward physics.

Biology has a logical meeting ground with chemistry. It is becoming ever more clear that facts long sought in vain by the methods of biology will yield only to the chemist, who is able to analyze the complex colloidal substances occurring in protoplasm and in the body fluids of plants and animals, and to study their chemical behavior and modes of interaction. More recently it has become evident that a meeting ground

exists for physics and biology. The rise of biochemistry and biophysics, with the more extensive application of the proved and powerful methods of chemistry and physics to biological problems, promises to serve as an antidote to excessive specialization as well as to promise the early solution of fundamental problems concerning the very nature of life, which under the methods of biology alone might be unattainable for decades or even centuries.

Strictly speaking, the application of chemical and physical methods to biological and especially medical problems is not new. Alchemy was originally a medical science. Since scientific chemistry displaced its unscientific ancestor the chemist's art has been continually at the service of the physician whenever medicines were to be prepared or natural drugs or herbs purified. The chemical analysis of urine is a more recent case in point. Nor has physics been isolated from the practice of medicine. It has been centuries since the temperature of the human body as determined by the thermometer, a physical instrument, was first used in diagnosis. The measurement of blood pressure, a routine procedure in the majority of medical examinations, depends on principles which once belonged exclusively to physical science. More recently the use of x-rays to discover broken bones, stray bullets, or other abnormalities in the human body has saved many a life, while the microscope used in making counts of blood corpuscles has become an important factor in clinical practice. Basal metabolism tests, in which the input and output of energy in

living animals or persons are measured with physical apparatus, has enabled many a person to be assisted back to health. Finally, the treatment of cancer with gamma-radiation from radium, or with x-rays, has held out renewed hope to multitudes.

In the field of original research concerning fundamental problems, on the other hand, it is clear that science is now standing on a threshold only to be crossed by investigations in biochemistry and biophysics, bringing to bear on biological problems the powerful methods of research that have been developed in both chemistry and physics.

The discovery of the hormones and vitamins, which really come under the head of biochemistry, has already been described. In particular has the chemistry of the hormones been important in leading to an understanding of body processes.

A little has been said in a previous chapter about the chemistry of protoplasm. In this case, as in the study of the hormones, recent advances are principally due to the increasing use of living animal cells or tissues in experimentation. The colloid chemist finds it a comparatively simple matter to analyze a sample of protoplasm, and to make a list of the chemical substances contained therein, with the numerical proportion of each. He can even tell much about the behavior of protoplasm under varying conditions. But this knowledge gives no indication why the substance can live and grow.

Is protoplasm a chemical compound or only a mixture? Does it owe its vital properties to its chemical

nature, or to some added essence that is only present when the material is alive? Such questions the biochemist is attempting to answer.

Leaving aside for the moment the question as to whether all properties of living cells and tissues can be explained in chemical and physical terms, a question to which we hardly possess the vaguest suggestions of a reply, and which may in its completeness be forever unanswerable, it is possible to consider how far chemistry is able to account for the observed behavior of plants and animals. It will be found that the laws of chemistry and physics will go a long way in explaining the properties and behavior of living organisms, and that in such organisms no chemical or physical laws are disobeyed.

Many of the properties of living material are intimately connected with substances called enzymes.

In general, enzymes may be looked upon as organic catalysts. An explanation of catalytic action has already been given. It may be recalled that a catalyst enables a chemical reaction that would not ordinarily occur to take place, or speeds up a slow reaction. The catalyst does not enter permanently in the reaction, and in inorganic chemistry at least is left unchanged after the reaction has gone to completion.

If it were not for the enzymes present in yeast, this country would not have had such a to-do about prohibition, for there would have been very little alcohol to prohibit. And without the enzymes present in the blood there would have been few persons on earth capable of drinking anything. Such persons as might

be alive would be too intent on getting a sufficient supply of oxygen into their body to bother about becoming intoxicated.

Enzymes thus take their place beside the vitamins and hormones as chemical regulators. They are necessary for fermentation processes, desirable or undesirable, and control the chemical change of sugars into alcohol. They produce wine from grape juice, and in many cases cause the spoiling of canned fruits and vegetables. Without enzymatic or some alternative action it would not be possible for the hemoglobin of the blood to take on oxygen for distribution to various parts of the body. Enzymes also control the ozygen intake of such simple (or should we say complicated?) living systems as single cells, which in most cases are not able to live and grow without a regular intake of oxygen.

Chlorophyll, the plant pigment responsible for the absorption and utilization of radiant energy, is a true enzyme. Chemically, chlorophyll is closely related to hemoglobin, the former containing magnesium and the latter iron, besides the ingredients common to both.

Much experimental work has recently been done by Willstätter and others on the nature of enzymes. Willstätter has found, for example, that most forms of plant pigment contain two sorts of chlorophyll which are differentiated by their differing oxygen content. The number of enzymes that are known is considerably larger than the number of kinds of chlorophyll.

What is the real nature of enzymes? They are organic substances, perhaps in some way related to bacteria. It is possible to analyze them, when they exist in such quantities that they can be separated and collected for analysis. The chemical constitution of chlorophyll is known. But neither chlorophyll nor any other enzyme has been synthesized. Enzymes must be considered as forms of living substance, for they are able to multiply in the processes of fermentation and respiration in which they play so important a part. And here it may be repeated that, although many substances such as urea which have been classed as organic have been synthesized in the chemical laboratory, no living substance has ever been so produced. Until an enzyme has been synthesized as a living substance it will be impossible to say exactly what an enzyme is. At present enzymes can only be described by their properties, a limitation which is also true of so many other entities studied in science, including the electron, a cell of protoplasm, and the human mind.

The recent discovery of heavy water by Nobel Laureate Urey and his associates has given biologists something to think about.

A molecule of heavy water consists of two atoms of hydrogen and one of oxygen. But the formula H_2O must be modified, in the case of heavy water, to read D_2O, D representing the new form of hydrogen, called heavy hydrogen, or deuterium.

Heavy hydrogen, because of its greater weight, and possibly other factors, is chemically less active than

the older orthodox hydrogen, a fact which has made separation of this new form of hydrogen possible. For example, it is left behind when water is electrolyzed: more of the ordinary hydrogen is liberated than the heavy hydrogen. This decreased chemical activity of heavy water led naturally to the question of its biological effects.

Experiments of Lewis in California, exponent of the Lewis-Langmuir Atom, soon gave a tentative answer to the question. Tobacco seeds were placed in water and allowed to germinate. In normal water the seeds made the best use of their opportunity, and sprouted. Those in water containing a considerable proportion of deuterium also sprouted, but not so profusely. Seeds placed in water in which deuterium predominated were not able to sprout. These failures, when later transported to a fresh bath of ordinary water, were in some cases able to germinate, but not in others. Similar observations were made with yeast cultures.

Following this lead, experiments were performed with protozoa and with flat worms. A moderate proportion of heavy hydrogen in the bath would slow down the vital processes of the animals, while water with a large proportion of the heavy hydrogen was in many cases able to kill the protozoa or the worms.

With the limited quantity of heavy water at his disposal, Lewis tried the experiment of feeding this water to a mouse. The experimental mouse showed unmistakable symptoms, becoming in a sense intoxicated, and apparently very thirsty. The very small

amount of heavy water available prevented further experimentation on the mouse. But as it becomes possible to obtain this water in larger quantities, similar experiments will be repeated. Heavy water may have a distinct effect on living organisms, and it is important to understand what the effect is, and why. No doubt facts of great biological interest will arise from such investigations.

Before passing to a consideration of recent work in biophysics, one more biochemical achievement must be noted.

The announcement of the separation of a substance called pantothenic acid, apparently connected in an intimate manner with growth processes, caused considerable notice and comment. The announcement was made by Williams and Lyman, of Oregon.

Pantothenic acid is apparently contained in all growing things, from yeast-mold to man. Its discovery followed an investigation of factors able to accelerate or retard the fermentation processes in yeast cultures. This acid when added to a yeast culture will enormously increase the rate of growth, and evidence points to its ability to control growth in many other organisms. Its very ubiquity points in this direction, for biologists familiar with nature's economy have learned that the mere presence of such a substance should not be neglected, but should be investigated until its function or lack of function is known in detail. This particular substance has many of the properties of a vitamin, but also possesses some properties which are not common to vitamins. Future research

will tell of its functional place in nature, as well as its own chemical constitution, and may lead to a new method for prolonging human life. At present it is one of the many biochemical perplexities, and as such a scientific challenge.

It is quite appropriate to begin any general discussion of biophysics with the subject of photosynthesis.

All theories purporting to give a more or less correct account of the origin of life on earth must assign a prominent part to the sun and to its radiation: visible, ultraviolet, or infrared. No discussion of the way in which animal and vegetable life is maintained on earth can dispense with solar radiation.

Photosynthesis is a general term denoting the building up of chemical compounds under the action of radiant energy. The subject is a special part of the science of photochemistry, a branch of physical chemistry.

When light falls on the silver compound on a photographic plate or film, as when the plate or film is exposed in taking a picture, a photochemical change takes place in the sensitive emulsion, so that the chemicals employed in development will bring out the picture in a permanent form. The exact mode of action of the light was not known until after the discovery of the photoelectric effect, mentioned elsewhere in this book. Now it is realized that the light sets electrons free from atoms in the silver compound, the energy given to the ejected electrons by the light finally becoming available in producing a chemical change in the exposed parts of the emulsion. The

process of vision depends on a photochemical action, an action by which radiant energy falling on the retina is able to produce a characteristic chemical action stimulating the optic nerve to transmit to the brain the sensation of sight.

Schoolchildren are introduced to photosynthesis at an early age. They are told how the energy of the sun is utilized by growing plants and how carbon dioxide is taken from the air and carbon stored in the plant fibers, all under the action of sunlight. They learn how the stores of carbon thus accumulated in past ages have been preserved in natural veins of coal and reservoirs of petroleum. Later they hear about chlorophyll and its significant role in natural economy.

Knowledge of the process of photosynthesis is not new. There are however certain points which have only recently been cleared up, and others that are still waiting for their solution.

It has long been known that chlorophyll absorbs certain portions of the solar radiation, those parts whose wavelength is rather longer than the average wavelength of visible light. Experiments on the absorption of light passing through a solution containing chlorophyll show that red light is absorbed, rather than light in the blue end of the spectrum. It was once supposed that chlorophyll was merely an agent responsible for the absorption and concentration of radiant energy in a form available for use in the growth of plant tissues. This statement really implies more than mere absorption, which alone would produce a rise in temperature, and something more is

clearly involved than mere rise in temperature. Lately it has been realized that chlorophyll plays a double role: not only is it an efficient agent for absorbing solar radiation, but it is as well an enzyme and plays the part of a catalyst. It is thus able to assist the plant in the production of more chlorophyll and protoplasm at the expense of the absorbed radiation, carbon dioxide from the atmosphere, water, and such inorganic substances as are obtained from the soil.

Recent experiments have served to clarify the processes of photosynthesis. It is a simple matter to enclose a growing plant in an experimental chamber and radiate it with light of a known wavelength or series of wavelengths. The gaseous products as well as the gases utilized in the process can be analyzed, and the quantity of each that is liberated or used up can be measured. The results of such detailed experiments must be of great importance in the formulation of theories concerning the origin of terrestrial life as well as its development. In connection with an examination of fossils and tree-rings they may be useful in studying weather conditions of past ages, for as is well known, the amount of ultraviolet and certain other components of the solar radiation reaching the surface of the earth depend on conditions in the atmosphere. At present the existence of ozone in the upper atmosphere limits the extension of the solar spectrum in the ultraviolet, and cuts off rays that would produce severe sunburn with little exposure, and undoubtedly severe damage to plants.

Experimental studies of the biological effects of

radiation have not been limited to photosynthesis. The effects of ultraviolet radiation and x-rays on plants and animals have been studied in detail and have led to interesting discoveries.

A little ultraviolet radiation, or a small amount of radiation in the still shorter wavelength region of x-rays appears to be beneficial to the growth of plants and lower animals. Stronger doses have lethal effects. Such lethal effects have been put to practical use in the purification of drinking water. The beneficial effects of sunlight on growing children in the prevention of rickets has been mentioned. Further, beside accelerating the growth of plants, radiation will enable certain plants that are used for food to produce quantities of vitamin D, which in the absence of direct personal exposure to sunlight or ultraviolet radiation will suffice to enable the growth of healthy bones. The presence of vitamin D in the eggs of hens and the milk of cows exposed to sunlight or ultraviolet radiation has also been mentioned.

To a subsequent chapter belongs a consideration of the so-called mutations produced by short wavelength radiation. It is even possible that mankind owes his present form to some such mutation away back in the evolutionary process. At present another subject claims our attention.

A few years ago an observation in a biological laboratory excited considerable scientific comment, as well as notice in the press. Reference is made to mitogenetic radiation, or as the supposed rays were called, M-rays.

The original observation was made by Gurwitsch, who noticed that two onion root-tips, growing side by side, appeared to have some mode of interaction which he ascribed to a sort of radiation. It appeared that one of the growing tips, when in the vicinity of a similar root-tip, grew faster on the side near the neighboring tip. Accordingly he assumed that radiation was emitted from a growing root, produced by the processes of cell division or mitosis always present in biological growth, whether of vegetable or animal tissue.

Much scientific controversy has followed this observation. Some investigators are unable to confirm it, while others have gone so far as to announce that they have detected this radiation by physical rather than biological means. An offshoot of the subject led to the statement that in certain cases cell division in animal tissues was able to produce similar radiation, detected in this case by the acceleration of healing in wounded tissue adjacent to the growing tissue used as a source of the assumed radiation. This latter case has recently been studied by Helff in extensive experiments on tadpoles, experiments performed with such a tremendous number of specimens and under conditions so carefully controlled that there remains little evidence to support the theory. In the case of the rays said to be emitted from vegetable matter, no final conclusion has as yet been reached. If, as does not seem entirely probable at the moment, the existence of these rays is verified, and is proved without ambiguity by physical measurements, the biologist will

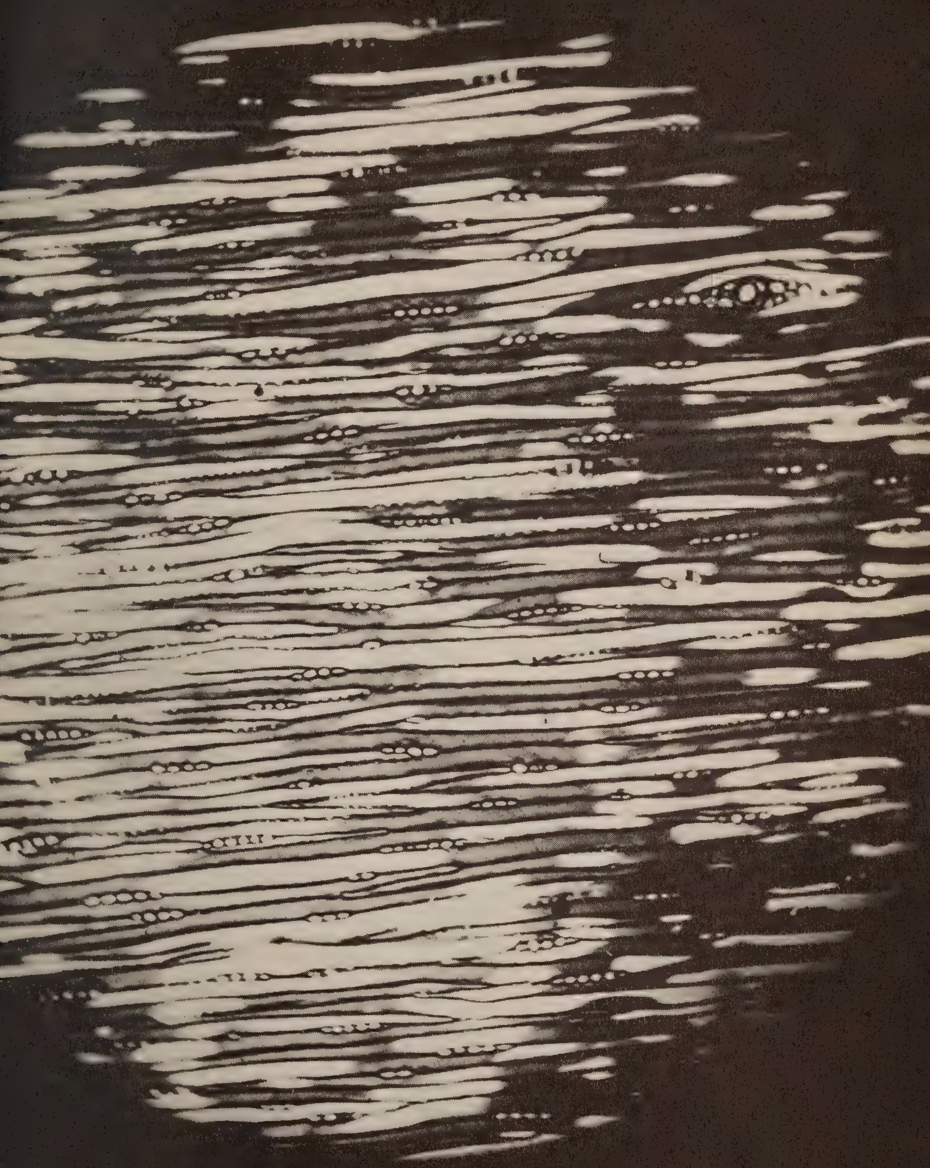


Plate XVIII
Wood fibers.

have something more to work with and to worry about.

The science of physics, as well as specialized physical apparatus, is more and more being brought to bear on biological problems, often with great success.

Many of the smaller forms of organism were not available for study until the perfection of the ultramicroscope. In this instrument small forms are made visible by concentrating an intense beam of light on the material that is to be studied. Objects not visible with the microscope when the light is sent up through the specimen in the usual manner become visible in the ultramicroscope, with intense light coming from the side, as bright objects on a dark field, brought into view by their disturbing action on the light waves in the intense beam. Although details seen with the ultramicroscope are not so clear as details seen under ordinary conditions with the usual form of microscope and larger objects, still it is better to see these small objects, however imperfectly, than not to be able to see them at all. Other modifications of the microscope enable the examination of solutions of transparent material with polarized light. Such observations have been made upon the properties of the filterable virus, with promising results. And no theory of the nature of life will be complete until the filterable virus is understood.

The ultracentrifuge, a new physical development of the always useful centrifuge, enables the scientist to achieve greater speeds of rotation and hence greater centrifugal forces. He is able to study the effects of

these huge forces on cells and colloidal substances, and to glean further information about their constitution and structure. The new instrument gives him more powerful means for separating substances and for distinguishing between materials which will not yield to less effective methods.

Much success has attended physical examination of diffusion and osmosis in studies promising to clear up difficulties in understanding the equilibrium of salts, acids, or alkalis in the blood and body fluids. It has been recognized that ions as well as neutral atoms and molecules may play an important part in these processes, and whether in animal tissue or in the roots of growing plants, the significance of these physical processes is being determined.

Cells, eggs, and more complex tissues are being grown in magnetic and electric fields, with results that are often surprising. The question always arises as to whether variations produced by such outside disturbances will be inherited, resulting in a new mutation and perhaps a new species. Much of this work is yet to be brought to a definite conclusion. Some of it which seems to be leading to understandable and significant results will be discussed in the next chapter.

No discussion of biochemistry and biophysics would be complete without a reference to the work of A. V. Hill, a physiologist who finds his work in these branches of biology so interesting that he is led to name a report on some of them, Adventures in Biophysics. Truly they are adventures.

Hill developed a sensitive thermopile, specially suited to his purpose of measuring temperature in muscle and nerve fibers. More than a hundred junctions between the two metals used were connected together in the usual fashion and the whole connected to a galvanometer. As has been mentioned elsewhere, thermocouples used in measuring the temperatures of stars and planets generally employ only two junctions, because the diameter of the telescopic image is so small. In Hill's work more junctions were needed, the heat developed in muscle being so small that one junction would not give an appreciable galvanometer deflection. Samples of muscle will cover an instrument of moderate size.

Muscle fibers were prepared by soaking in a solution known as Ringer's solution to keep them in a state suitable for the experiments. Later the solution was drained off and the muscle fiber, lying on the thermopile, was stimulated and caused to twitch. This artificial exercise of the muscle produced changes similar to those in muscle intact in a living animal: phosphagen in the muscle was used up and lactic acid formed, and heat was developed. It was the relation between the amounts of these various changes that was being sought.

An unexpected observation nearly led to a new and startling physiological theory. It appeared that heat was being developed by resting muscle, keeping the muscle at a higher temperature than the surroundings. But unexpectedly, and just in time to prevent the announcement of the new physiological theory, came the

explanation: Chemical changes in the muscle after stimulation altered the osmotic pressure in the muscle, which in turn altered the conditions of equilibrium of the water vapor in the experimental chamber. It was the condensation of water vapor which caused the observed temperature changes.

One thing leads to another, in biology as in the larger field of human affairs. From this narrow escape Hill was able to develop, with the use of his thermopiles, an extremely sensitive method for studying vapor pressure in small amounts and under conditions in which the pressure changes are extremely small. This technique has led to further advances in the understanding of physiological processes.

More recently Hill has been studying the effects of nerve stimulation in an attempt to understand the pulse or signal which travels along a nerve.

Nerve pulses have associated with them a sort of electrical wave, which in some instances can be detected by the electrical instrument called the oscillograph, an instrument which shows the magnitude of an electrical effect and its changes with time. In species such as the electric eel these electrical effects may be additive so that a distinct shock can be produced. Other experiments have shown that the eyes of frogs and toads, severed from the animals, and connected by means of the optic nerve to an electrical amplifier, will produce a measurable electric current when light is shined on the eye. In the stimulation of a nerve and the passage of the nerve pulse, heat is also produced, in amounts small but easily measured

with the thermopiles developed by Hill. In many such cases measurement of heat and electric current can be carried to a greater accuracy than can chemical observations on the effects of muscle and nerve stimulation. Electrical effects in nerves are probably caused by chemical changes and vice versa. In fact the mediator between nerve and muscle is believed to be of a chemical nature, the stimulation of muscles probably being directly due to a chemical substance liberated on the arrival of a nerve pulse.

Thus the application of chemical and physical methods to the problems of biology and physiology is giving new and important information which will, it is hoped, lead to a more correct and complete understanding of physiological processes. The use of such methods in biology is so recent that much remains to be done, and few of the problems now being investigated can be said to have been carried to completion. Perhaps no single result as significant as some of the recent discoveries in other fields has as yet been attained. But it is clear that, when and if it becomes possible to understand the nature of life and the true difference between living cells and dead cells, or between protoplasm and inanimate colloidal substances, these and similar researches will have had a large part in the achievement.

CHAPTER XIX

RACE-MOULDING UNDER THE MICROSCOPE

HUMAN beings, as well as animals and plants, exist in great variety. A person may be male or female, light or dark, intelligent or feeble-minded. No two persons are exactly alike in every respect, each has some feature or trait which serves to distinguish him from every other person that has ever lived.

Many persons have probably asked themselves: How did I get that way?

In an earlier section of this book has been mentioned the role played by the endocrine glands and by their secretions, the hormones, in the control of growth and development. The attainment of normal physical and mental maturity requires the normal functioning of the thyroid and the pituitary glands, the adrenals, the pancreas, and many other glands capable of giving the small but indispensable amounts of their characteristic secretions to the blood. The development of the secondary sex characteristics and the control of the sex cycle in females depends on hormone action. But a further question remains: How, in the beginning, did the individual come to be a female, and not a male?

It has been less than a century since the monastic Mendel performed his classic experiments in pea culture. His experiments gave the first clear indication

of how individuals "got that way." Since then, further developments along the general lines of Mendel's investigations have made possible in a majority of cases a minute understanding of the facts of inheritance and of individual differentiation.

The classic experiments of Mendel have been described so often that it will only be necessary to mention them briefly.

Mendel crossmated two species of pea plants, one tall and the other short. The first generation resulting from the cross consisted exclusively of tall plants. But these tall hybrids were not identical with the original tall species, for the next generation, descended from the tall hybrids, contained both tall and short individuals, in the proportion of three tall to one short.

Thus whereas the original species of tall plants produced nothing but tall descendants, even unto the seventh or the seventieth generation, the descendants of the hybrids turned out to be both tall and short, the numbers of each being given on the average by definite and constant ratios in succeeding generations.

From these experiments arose the conception of what have been called Mendelian elements or characters. In the pea plants studied by Mendel, tallness and shortness were such elements. Of these two associated characters tallness triumphs over shortness in the hybrids, the first generation derived from the original pure strains. Tallness is accordingly called a dominant Mendelian element and shortness a recessive element.

The idea of dominant and recessive elements leads directly to an explanation of the inheritance ratios observed first by Mendel and since by multitudes of others. Representing dominant elements by capitals and recessive elements by small letters, and writing T for tallness and s for shortness, one arrives at the following classification:

The pure strains of pea plants contained either TT or ss, and bred true to type, tall plants fertilized by tall plants resulted in nothing but more tall plants. A similar thing was true for short plants fertilized by short plants. When tall and short plants were crossed, individuals containing the groups Ts resulted. These individuals were all tall, since T is dominant and s recessive. The immediate descendants of the hybrids contained one of the groups TT, Ts, Ts, ss. The group Ts is repeated because there are two chances for its formation for every one of TT or ss. The first three of these groups will result in a tall plant, again because T is dominant and s recessive. But the fourth individual, ss, will be short. Thus is explained the ratio, in the first generation of offspring from the hybrids, of three tall to one short.

Mendel verified his theory by other experiments, such as crossing hybrids with the pure strain, and carried his experiments through many generations.

More than one pair of associated characters are generally present in a given species. Peas are not only tall and short, they may be green or yellow, wrinkled or smooth. Mendel concluded that each pair of characters was independent of the others, and that

his laws of inheritance could be applied to each pair separately. He could thus determine in advance how many individuals of a given generation derived originally from hybrids would appear as tall plants bearing green and wrinkled peas. That this idea of the independence of pairs of associated characters has been modified in the light of more recent knowledge will appear below. It is, in fact, a sort of first approximation to the truth, being true in a majority of cases but by no means in all.

Slowly the ideas of Mendel gained acceptance as others repeated his experiments on different species and verified his results. Out of this work has grown the idea of the gene, the basis for a truly scientific and quantitative science of genetics.

Although it was at first believed by some that single genes were responsible for the inheritance of single Mendelian characters, the idea is no longer held. It is now known that many genes, acting through some sort of biological cooperation, are responsible for the inheritance of single characters, and that certain genes may, in cooperation with various other genes, be responsible for several distinct characters.

But what is the gene, and where is it to be found? How may it be studied, and how does it accomplish its work? The answers to these questions have been obtained in part from recent investigations. It is hoped that researches now under way may lead to more complete knowledge.

Before discussing the gene in greater detail it will be necessary to turn our attention for a moment to a

single cell. By watching the cell as it divides and multiplies, a great deal may be learned about the unit of inheritance, as well as about the reasons underlying the laws of inheritance formulated by Mendel.

Consider a single cell, such as the human egg just after fertilization. In other words, consider yourself when you were very young.

The cell has a number of easily recognizable features. It consists essentially of a mass of protoplasm bounded by a membrane. Inside, near the middle, is the nucleus, containing material called chromatin.* Near the nucleus is a small body called the central body or centrosome. Other parts of the cell need not at present detain us.

When the cell is ready to divide, two centrosomes appear, at first close together, later gradually receding from each other. Radiating from each centrosome appear streaks, like the rays often included in childish drawings of the sun. As the centrosomes move apart, certain of the radiating streaks remain common to both, forming a spindle, the so-called mitotic spindle. (This process of cell division is called mitosis. During these changes the nucleus has expanded slightly.

When finally the centrosomes are separated by a distance comparable to the radius of the cell the nucleus has begun to lose its identity. The chromatin forms itself into thin strings which break up into rod-

* The names chromatin and chromosome are due to the behavior of the corresponding elements of the cell when dyed for microscopic examination. They become highly colored.

shaped bodies of various lengths, called chromosomes. The nuclear wall has now disappeared, leaving the two centrosomes, one on each side of the cell and connected by the mitotic spindle, each the radiant of the streaks previously mentioned. Halfway between, the rod-shaped bodies or chromosomes are moving about and finally come to rest arranged around the cell at the equator, the plane at right angles to the central line of the mitotic spindle and midway between the two centrosomes.

At this stage the cell has become elongated, and begins to pinch together at the middle. The chromosomes split lengthwise, so that half of every part of each, whether the end or the middle, is retained in each part split off. Any material that is arranged along the length of the chromosome will thus be equally divided. This mode of division is important, and will be mentioned again.

The half-chromosomes move toward the centrosomes. The cell pinches still more and finally separates, each daughter cell containing half the protoplasm of the original cell, one of the centrosomes, and an even share of chromosome material. This material collects and forms a nucleus containing chromatin, as in the original cell before mitosis commenced. The centrosome takes its place on the nuclear border. Now there are two cells instead of one, each similar to the parent cell.

You have now grown a little older. Soon each cell will divide again, and four cells will remain. A repetition of the process, continued almost countless times,

has at last resulted in yourself, or your pet cat, if that had been the kind of cell under consideration.

For reasons which will soon appear it is known that the chromosomes are the bearers of the genes. A single gene is far too small to be visible under a microscope even with the greatest magnification obtainable.* A gene is believed to be somewhat smaller than a protein molecule, which as molecules go is rather large.

Various species of plants and animals have different numbers of chromosomes. Man has forty-eight, or more correctly, forty-six plus two.

Two of the chromosomes in any human individual, as well as in higher animals and plants, appear to be set apart from the remaining chromosomes. These chromosomes are called *X* and *Y*. The female has forty-six chromosomes plus *X, X,* while the male has forty-six plus *X, Y,* making in either case forty-eight in all.

The behavior of these *X* and *Y* chromosomes determines the sex of the offspring, as well as many inherited characteristics which for reasons that will soon appear are said to be sex-linked.

Before describing the process of sex-inheritance it will be necessary to return for a moment to the subject of cell division.

In discussing mitosis it was remarked that the mode of division of the chromosomes was significant. In

* In the salivary glands of Drosophila (fruit-fly) larvae are found giant chromosomes which are visibly segmented. The segments may be either genes or gene-loci, probably the latter.

this form of cell division the chromosomes split lengthwise so that each daughter cell possesses as many chromosomes as the parent. But in another form of cell division, called meiosis, a different situation occurs.

Meiosis occurs when the germ cells, egg or sperm, are formed in the adult individual. In this particular mode of division the chromosomes are so divided that half go to one cell and half to the other. In the case of human beings the developed egg or sperm thus contains twenty-four chromosomes, or twenty-three plus one. This mode of division is a happy provision of nature to allow the fertilized egg to have the normal number of chromosomes, forty-eight, and not twice the number. If the number were allowed to multiply it would multiply indefinitely and without limit, which would result in leaving the mechanics of inheritance in quite a chaotic state.

Suppose that eggs and sperms are ready for fertilization. Every egg possesses twenty-three chromosomes plus *X*, while half the sperms possess twenty-three plus *X*, and half twenty-three plus *Y*. If the combination of egg and sperm in the process of fertilization results in a fertilized egg containing *X, X,* then a girl will result, whereas if the combination were *X, Y,* a boy would be produced. Since the number of sperms containing *X* and *Y* are about equal, the chances for the birth of girls and boys are on the average nearly the same.

The *X* and *Y* chromosomes, along with the others, contain genes, and would thus be expected to play a

part in determining the inheritance of the offspring. This is actually what happens.

Suppose that the genes in one X chromosome are such as to lead to some defect in the offspring. The disease of hemophilia, or bleeding, is due to such a defect in the genes of the X chromosome. Let us call the defective chromosome X'. Then when the egg from an individual carrying X' is fertilized, the possibilities are as follows: $X, X; X, Y; X, X'; X' Y$. Of these, the last combination will produce a diseased child, while the first three will not. The inheritor of X, X' will, however, be able to pass on the defective X' to further generations.

The interesting fact is that X is dominant as compared to X', but X' is dominant as compared to Y. Accordingly boys will show the disease and girls ordinarily will not.

Such are the known facts regarding this disease, facts which are amply explained on the theory of sex-linked inheritance which has been outlined. Theoretically it would occasionally be possible to produce the combination X', X', a diseased female. That this combination occurs rarely, if ever, may be explained by the probable early death of such children, due to some lethal gene in X' which only become fatal when strengthened as in the doubled combination X', X'. The Y chromosome appears to be in a sense decadent, allowing the X' chromosome to become dominant over it. A similar fact may have something to do with the slight inequality in the number of girls and boys which are born healthy.

Much of the present knowledge in the field of genetics is a result of the work of Morgan with the fruit fly, Drosophila melanogaster, and similar investigations prompted in many cases by Morgan's experiments.

The fruit-fly was chosen because it multiplies rapidly. A rapidly breeding species is a necessity since in any genetic study one must breed and crossbreed, noting the results in many successive generations of offspring.

These and similar experiments have shown the intimate relation between the chromosome and the gene. In contradiction to Mendel's belief, it has been found that pairs of characters, such as dark or light skin, brown or blue eyes, are not independent in the mechanics of inheritance. Certain characters tend to appear together, giving rise to the concept of gene-linkage. Genes are arranged in linear order along the chromosomes, so that the chromosomes are essentially gene-linkages.

In mitosis, the length-wise splitting of the chromosomes to which attention has previously been called provides that all the genes in one chromosome will be shared equally between the daughter cells. In meiosis, on the other hand, the process in which the germ cells are prepared, the chromosomes divide in such a way that part of the genes in a given chromosome go to one cell and part to the other. In this way the genes, units of inheritance, are divided. Different germ cells have different genes, and variety of descendants is provided for. If all germ cells of each individual of

a pair who are producing offspring were identical in their gene content, all children of this pair would be as alike as identical twins. The segregation of Mendelian elements or characters is thus explained by the combination of genes and gene-linkages which happen to be included in the fertilized egg.

Occasionally a gene-linkage will be partly destroyed, so that the linkage is altered, or part of it joined to another linkage. This is called crossing over, and while not as yet completely understood, has been able to explain many factors observed in the study of inheritance.

It has been possible to determine which genes are present in each linkage, and their arrangement, as well as an idea of the actual physical size of a gene, from studies of inherited characteristics in many generations. A rough estimate of the size is obtained by dividing the size of a chromosome by the number of genes known to be present. This size, as has already been mentioned, comes out slightly smaller than the size of a protein molecule. It should be remembered that knowledge of the number of genes is not in any sense complete. Accordingly the estimate of size is probably in error. It may be considered as a limiting case.

One of the greatest problems in genetics has been the problem of mutations. Every biologist who has ever done any work on evolution has had a guess as to the solution, and many replies have been given. The problem, reduced to its simplest form, is something like this: What is the reason for the sudden and un-

expected appearance of new characteristics which have never appeared in previous members of a species, but which may in some cases be inherited and become one of the distinguishing features of the species? In other words, how do new species originate?

It is not difficult to produce artificial mutations, but in animals, and in most cases in plants, these mutations are not inherited. One is reminded of older breeding experiments in which wild flowers, when domesticated and bred for genetic examination, could be made to take on new characteristics, which however promptly disappeared when the flowers were returned to their normal habitat and conditions of wild growth. The changes under domestication were apparently caused by conditions favorable to the appearance of characters already present in the germ cells and their chromosomes.

Mutations of many kinds have been produced by the use of x-rays, ultraviolet radiation, high temperatures, and manual or chemical alteration of the fertilized eggs. Some of these changes are of the type classed as crossing over, some are more complicated. A consistent examination of many such cases will furnish information as to what stage in embryological development is responsible for the appearance of the observed mutations.

But the genes are not the only factors involved. It has been mentioned elsewhere how the presence of the proper hormones will allow a young girl to grow and develop in a normal and healthy manner, whereas in the absence of these hormones the development of sec-

ondary sex characteristics will not be complete. By the use of the appropriate hormones in experiments, especially on laboratory animals, changes have been produced amounting in some cases practically to a change in sex.

It is not yet entirely certain which roles are played solely by genes, which solely by hormones, and which by the two acting together. Surely the genes in the chromosomes of the fertilized egg determine the main path of development, a development which is accelerated, controlled, or altered by hormone action as the embryonic growth advances and the individual attains maturity. No doubt the hormone action itself of the developed individual depends on the gene constitution of the original cell.

The characteristic genes are present and remain active throughout the life of an individual. If a man cuts his finger, the genes provide that the cut will heal with the formation of new human skin, not some other material such as chicken feathers.

The newer knowledge in the field of genetics is beginning to have its repercussions in related sciences. It appears to promise an explanation of the origin of species and of the problem of individual variation, problems which have vexed many workers in biology, including the great Darwin. A start is being made in its application to anthropology, concerning the question of differences between races of humanity. In this connection a related study is being applied with some success.

From studies of blood transfusion it has been found

that there are four general blood types. If blood of different types is mixed, a characteristic reaction occurs which has been used in court when the parentage of a child is under dispute. In blood transfusion, if success is to attend the operation, the blood of the donor must be of the same type as that of the recipient. The study of blood types has been extended to an examination of racial differences, and in some cases may be depended on to distinguish a group of individuals as to race when other tests fail.

A start has been made in the application of genetics to the broader science of eugenics. The selective breeding of cattle has long been practiced. New species of seedless grapes, disease-resistant bananas, and smooth barley have recently been developed by selective breeding, in each case producing a new product more suited to the economic and other needs of the producer and the public. The hope that similar successes may be attained in the breeding of more healthy human beings has sometimes been strengthened by genetics, and sometimes weakened.

The immense number of genes in a single individual and the complexity of their arrangement and combination has clearly shown the impossibility of preventing the inheritance of undesirable characteristics by preventing the propagation of the bearers of defective genes, even if carried out for many generations.* The characteristics derived from defective genes may be recessive for decades or even centuries,

* A bearer of defective genes can only be detected by the quality of his descendants.

only to pop up when a suitable combination of two individuals bearing these defective genes leads to an offspring bearing similar defective genes obtained from both parents. For certain undesirable inherited characters, such as feeblemindedness, sterilization may be effective. The case is different for other abnormalities, because their inheritance may not be entirely certain and because desirable qualities which may be more certain to be passed on to future generations would at the same time be eradicated. Too little is known about the complex genetic constitution of human beings. With the sterilization of all feebleminded persons, it would be years, perhaps hundreds of years, before feeblemindedness could be completely wiped out. Even then, some recessive character or combination of characters, or even a new mutation, might produce more individuals of the undesirable type.

It is the hope of geneticists that sometime they may learn enough about the factors of inheritance, and the manner in which these factors become effective in controlling the development of the individual, to be able to control inheritance and produce individuals according to specification. The present methods of eugenic breeding allow some degree of control, although the process is relatively slow. Will the time ever come when manipulations of cells and their constituents under the microscope will enable the production of individuals having any desired characteristics?

Plate XIX

Mitosis. The chromosomes are beginning to split.

CHAPTER XX

THE ORIGIN OF LIFE

How, it will be asked, is it possible to speculate on the origin of life when the very nature of life itself is at present largely a mystery?

The only possible reply is to be found in the history of science: many epochal investigations have been undertaken with no greater promise of success. If the result could be foreseen, there would not be so much fun in the venture. But even if the biologist should abandon the problem as too difficult, he would soon be driven back by the clamor of the public, demanding at least an attempt at a solution. Finally, the biologist is driven toward the problem in self-defense, for if he neglected the search for knowledge of the origin of life, others would put forward their theories, scientific or unscientific. The biologist must see that such speculations are not in contradiction with known biological facts.

The theory that organic life on earth originally developed from inorganic substances has met with considerable support among biologists.

After the earth had cooled so that at least the outer crust was at a moderate temperature, a large part of the surface was covered with water. The atmosphere contained water vapor, carbon dioxide, nitrogen, and some ammonia, but probably very little oxygen. The

oxygen now present has been derived from the carbon dioxide, the carbon being deposited in the form of rocks containing for example calcium carbonate, and in veins of coal, as well as in deposits of petroleum. In this process the growth of vegetation has played a prominent rôle. The process of photosynthesis, previously mentioned, occurring in the green leaves of plants under the catalytic action of the enzyme chlorophyll and of solar radiation, separates the carbon and the oxygen from carbon dioxide, liberating most of the oxygen and causing the deposition of the carbon. A comparison of the quantity of oxygen in the atmosphere with the amount of carbon believed to lie in the earth's crust leads to the belief that nearly all our atmospheric oxygen has been derived from carbon dioxide originally in the atmosphere, in far larger proportion than at present.

In the absence of uncombined oxygen in the atmosphere, more of the ultraviolet radiation from the sun would be able to reach the earth's surface. This portion of the sun's radiation is at present shut out by ozone, a substance whose molecule contains three oxygen atoms instead of the more usual two. Most of this ozone lies at present in the upper regions of the atmosphere.

It is known that, in the presence of strong ultraviolet radiation, molecules of carbon dioxide and of water will react to form simple carbohydrate molecules, such as those of sugar and starch. If ammonia is present, even more complicated organic molecules may be formed, approaching in complexity the large

protein molecules. In this sense organic material may be formed from inorganic. The organic material is not as yet, however, alive.

In time a considerable amount of organic material could be formed, producing a supply of food substances amply sufficient for any simple forms of life that might be present, or that might appear. The belief is that, under the action of the strong solar radiation, particularly the part in the region of shorter wavelengths, one or more of the complex molecules became sufficiently complex to enable it to show some of the properties of living substance. If this did in fact occur, many factors would favor its growth and further development. It would have an ample supply of food, and little or no competition. Whether one or more such molecules appeared is an open question; probably only one such molecule was able to live and multiply, for all substances now present in living forms affect polarized light in the same way and rotate the plane of polarization in only one of the two ways that are possible and observed in inorganic substances, and in simple organic substances like sugars and starches.

Once a single molecule became alive, the rest was only a matter of time. It is only necessary to assume the validity of the theory of organic evolution to account for the variety of forms of life, whether vegetable or animal, with which the earth is now populated.

The best that research can do at present in attempts to understand the origin of life is to study primitive forms. In order of increasing complexity and organ-

ization, one might list primitive forms as follows: enzymes, filterable viruses, bacteriophage, bacteria, protozoa, and multicellular plants and animals of which the highest type is the animal, man.

Bacteria are perhaps the most primitive forms which are certainly alive, although processes occurring in the still lower forms listed resemble the processes of life in some respects.

Enzymes, such as those present in yeast which make fermentation possible, as well as the filterable viruses and bacteriophage, are unable to multiply by themselves. Enzymes multiply in the process of fermentation, the viruses only in producing their characteristic action on higher forms, as when a human being contracts a disease caused by such a virus. Bacteriophage multiplies when destroying bacteria. Bacteria and protozoa are able to multiply by cell division provided only that the conditions of temperature and other physical and chemical quantities are suitable.

Accordingly it is somewhat difficult to decide whether the forms lower than bacteria are in reality alive. Ultraviolet radiation is far more destructive of bacteria and of the higher forms than of those forms below the bacteria. Some such fact may account for the existence of semi-living cells in the early days when the sun's radiation as received on earth was much richer in ultraviolet than it is at present. It is furthermore conceivable that, although such forms as head the above list are apparently not able to reproduce in the biological laboratory without the aid of something outside themselves, they may have

been able to do so in the simple and favorable conditions prevailing when the world was new, always granting a sufficiently long time, which of course is quite reasonable.

In this connection it is interesting to note that the human embryo, which in its development follows the general line of evolutionary development throughout the ages, exists during the first few hours of its life in the entire absence of available oxygen. Growth during this period is quite similar to the process of fermentation, which proceeds under so-called anaerobic conditions, in the absence of oxygen. Perhaps this stage of embryological development shadows the very earliest period of terrestrial life.

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